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FINAL REPORT

IDENTIFY FUTURE RESEARCH NEEDS IN WALL ENVELOPE TECHNOLOGY

by

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INTRODUCTION

The Army is facing an enormous problem with the vast number of Army facilities in need of repair, maintenance, replacement and modernization, of wall surfaces. It is acknowledged that there are limited resources available to accomplish such needs. However, through the adoption of new technologies it is anticipated that immediate cost savings or long term life-cycle cost savings will accrue. A thorough understanding of existing wall system technologies is essential if existing Army facilities are to be fully utilized. Therefore, in an attempt to review the existing body of knowledge the Construction Research Center at Georgia Institute of Technology was commissioned to write a report on the future research needs in wall envelopes. The following report outlines the results of that research.

The initial work comprised of a bibliographic search for information on existing wall system technologies and their related building defects. The search included reference to standard construction texts, journal articles, trade association publications and contact with research bodies. However, during the early stages of the work it soon became evident that many of the more common wall envelope building failures related to traditional wall systems. Thus leading one to surmise that the existing body of knowledge on walling technology was either being ignored or misinterpreted. In other words, simple problems that had been resolved many years ago were still being "built-in" to new work. Building failures relating to "newer" systems were more difficult to identify perhaps due, naturally, to their more recent introduction. (Most building materials and systems are relatively robust, and failure patterns tend to be identified only gradually.)

Therefore, the report has concentrated on a review of current walling systems, as well as commenting on "new" technologies. An emphasis has been directed towards the more common building failures. However, with such a wide ranging topic it has been difficult at times to be totally comprehensive and, hence, some topics have been treated relatively lightly. However, references are included in the text for a more detailed study. Finally, the study is limited to light construction, e.g. residential type buildings, single story industrial, and light commercial.

WALL ENVELOPE SYSTEMS

The primary function of an external wall is to act as a modifier of climate, e.g. it must ensure that the building is wind- and weather-proof; it must regulate the transmission of heat, light, sound, water vapor, fire, dust and smoke. In addition, due regard to constructability, structural support and cost should also be noted. In summary, the walling system should provide:

* adequate structural strength to support dead loads (the other building elements which it supports) and live loads (such as from wind and earthquake and from live loads from other building elements supported by the wall).
* weather-tightness to control the flow of heat, moisture, air and water vapor.
* satisfactory levels of sound and visual privacy.
* suitable fire resistance.
* the accommodation of heating, air conditioning, electrical and plumbing equipment.
* suitability for the application of various finish materials.
* adaptability to economical methods of assembly and erection.
* provision for the installation of doors, windows and other openings.

In addition, an external wall must be durable. Durability is dependant upon the physical characteristics of the materials and components adopted; the environmental conditions to which they are subjected, particularly with regard to intermittent rain soaking, solar radiation, freeze-thaw cycles, moisture and thermal movement; chemical reactions; wear-and-tear. For example, intermittent rain soaking may cause sulfate attack on brickwork; alkali-silica reactions in concrete; corrosion of ferrous fasteners and wall ties. If the wetting cycle is prolonged, destructive freeze-thaw cycling in porous materials such as brick or stone may result. In extreme cases, moisture from partial rain penetration may spread to internal finishes.

Prolonged exposure to solar radiation may also cause surface finishes to crack, craze, delaminate and, in the case of some polymeric materials, to become brittle. In a well insulated building the temperature on the outer layer of a wall may fall below freezing. Where moisture vapor is entrapped within the structure of the wall, damage may occur due to freezing. In addition, interstitial condensation may cause ferrous metal ties, fixings and reinforcement to corrode. All factors that influence the life-cycle of any building system or component.

Moisture Exclusion

The control of rainwater may be considered to be the prime factor in determining the success of a wall envelope. The way in which rainwater acts on a wall cladding depends on a number of local conditions, including the rate of rainfall; effects of wind; absorbency and moisture storage capacity of the surface material. For example, rainwater striking a masonry wall will be absorbed until, finally, a film of water is formed on the wall. When the rain stops this film dissipates and, as the wall dries out, the water absorbed slowly evaporates. On the other hand rainwater striking an impervious surface forms a substantial film of water that flows across the outer face of the wall cladding. Under the combined effects of gravity and wind action, much of this flow is concentrated at those places in the wall cladding where surface irregularities, such as joints, occur, (Figure 1).

Research indicates that the action of the wind causes a lateral migration of the water film, which concentrates the downward flow along the lines of vertical protrusions and depressions. The flow of water in recessed vertical joints is therefore many times greater than the average flow across the wall. The smoother the wall surface and the greater the distance between vertical joints, the greater the concentration. Additionally, wind may force rainwater upwards into horizontal joints.

External walls may be categorized according to the way in which they resist rain penetration, i.e. mass walls, fully-sealed, rainscreen or protected walls.

<u>Mass Walls</u>: solid walls control moisture penetration through absorption; the wall absorbs and retains the moisture until the rain stops, and the stored water then evaporates. Traditionally, solid walls are constructed from smaller units with mortar joints, which usually develop numerous micro-cracks in response to loading, aging, and thermal - moisture movements. The performance of a masonry wall may be improved by the provision of a discontinuity or air-space, e.g. a 2" (50mm) cavity in a brick wall.

<u>Fully-sealed walls</u>: fully sealed walls of relatively impervious materials, such as metal and glass, are designed to drain off all rainwater at their outermost surface. All joints need to be permanently weather-tight, a potential weakness since repeated thermal movement may result in joint failure. In addition, fully-sealed walls demand high standards of installation, inspection, maintenance and replacement programs if they are to maintain their rainscreen integrity.

Long-term performance of fully-sealed walls can be improved by introducing an airspace immediately behind the sealed outer face. (The cavity provides an air-space which can be drained to the exterior, a typical feature cavity masonry construction and most metal and glass curtain walling systems, (see later discussion on masonry cavity construction and rainscreen cladding systems.)

Economics of Walling Systems

The ultimate costs of a wall system include in-place costs, maintenance costs, operating costs and replacement costs. In-place costs are the sum of the costs of materials, labor and overhead required to assemble and/or install the system. In addition, the selection of a wall system may also affect other costs, such as installing insulation and a vapor barrier, applying siding or other finishes and providing for window and door openings. Maintenance costs and operating costs attributable to the wall system (such as heat loss or gain through the construction) have an important influence on the ultimate cost of the wall and should not be overlooked if long-term economy is to be achieved. The life-cycle of the building and walling system also need to be evaluated in an attempt to determine the replacement cost of the full or partial walling system during the anticipated life of the building project.

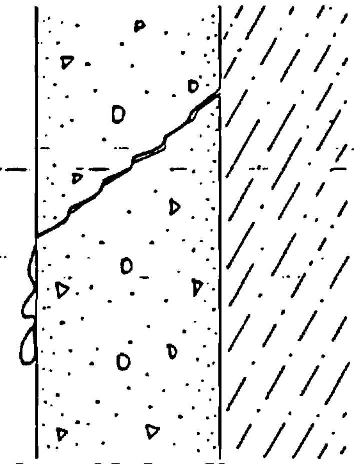
Generally, wall systems are covered with applied materials which provide the desired finished appearance and performance. The selection of finish materials may also influence the cost of the walling system by:

* affecting the spacing and span of the primary structural members.
* determine the need for wall sheathing and/or other finish bases.
* dictating the kind, type and physical properties of the subsurface materials.
* imposing a preferred construction method.

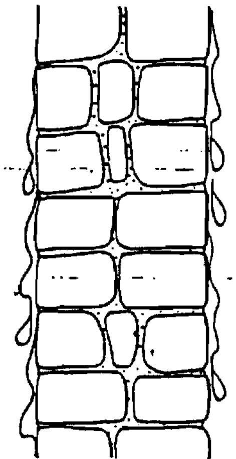
Rarely are walls for light residential and commercial buildings specifically engineered. Ordinarily, building codes or rules-of-thumb based on established practices determine materials and methods of construction, (Appendix 1).

Typical wall systems to light residential and commercial buildings include a number of conventional systems, e.g. stud wall construction, either "stick-built" or panelized (platform frame); masonry construction and light steel- and concrete-frame construction, (Appendix 2).

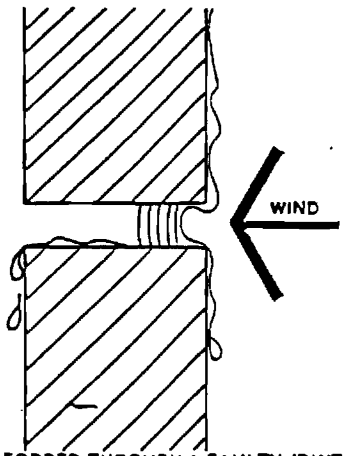
Figure 1



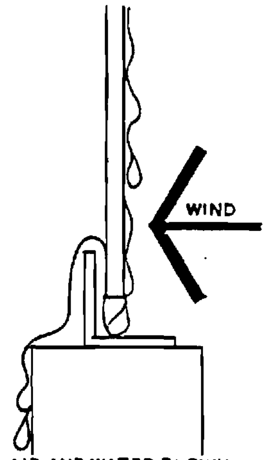
WATER FLOWING TO THE INTERIOR THROUGH IMPERFECTIONS IN THE BUILDING ENCLOSURE BY THE FORCE OF GRAVITY



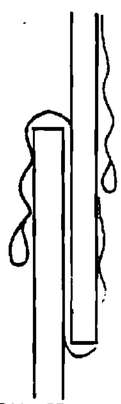
EXTERIOR MOISTURE SUCKED THROUGH A POROUS BARRIER BY 'WICKING' ACTION



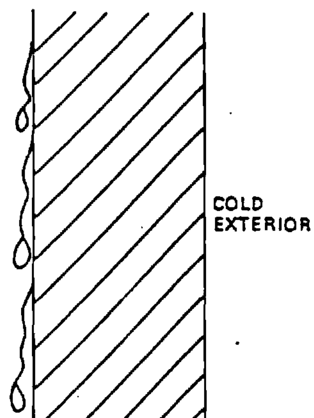
WATER FORCED THROUGH A FAULTY JOINT BY A COMBINATION OF WIND PRESSURE AND PRESSURE DIFFERENTIAL



AIR AND WATER BLOWN OVER A BARRIER.



CAPILLARY ACTION. WATER IS DRAWN TO THE INTERIOR THROUGH SMALL OPENINGS.



CONDENSATION. WARM MOIST AIR IN CONTACT WITH A COLD SURFACE DEPOSITS MOISTURE AS IT DROPS IN TEMPERATURE.

TIMBER FRAME SYSTEMS

The following discussion of conventional stud wall construction refers to "stick-built" erection methods, i.e. where carpenters on the job handle individual studs, and prefabricated panel systems, (Figure 2). (Panelized systems are common in the U.S., with approximately 40% of all new dwellings incorporating off-site manufacture of wall systems. These are incorporated into manufactured homes; modular dwellings as well as the more conventional platform-frame dwelling constructed on site. Their properties, however, are similar to "stick-built" buildings.) Further information on assembly techniques may be obtained from references(1,2) and Appendix 3 on "house building basics"(3).

Because of the existing body of building codes and other regulations and practices, detailed engineering design is rarely required for timber-framed systems. For example, the conventional 16" and 24" spacing of studs has evolved from years of established practice and is based more on accommodating the finish materials applied to the framework than on actual engineering for imposed loads. In one-story residential construction, 2" x 4" studs placed at 6' intervals would adequately support the generally imposed roof loads. But few exterior or interior finish materials can span such intervals economically. The 16" and 24" spacing permits the use of standard widths and lengths of panel sheathing and siding and hence remains the convention in use. In stud systems, roof and other vertically imposed loads are carried by the studs. Sheathing and applied finishes resist lateral forces but are not assumed to share in carrying vertical loads.

Wood stud systems lend themselves to on-site or off-site fabrication. Stud wall systems provide flexibility in design and erection and require only the use of simple hand tools and fastenings. Change can be made easily during construction, particularly with on-site fabrication. Space between studs provides for the installation of insulation and heating, air conditioning, electrical and plumbing equipment. Studs may be erected by themselves or framed on the subfloor with sheathing and siding applied and windows and doors installed. The assembly then is tilted into place.

Wood stud wall systems are also economical. They provide excellent structural performance, make use of relatively inexpensive basic materials, permit the application of many finishes and are adaptable to practically any methods of on-or off-site fabrication.

Panelized systems share many of the same design characteristics of stick-built buildings. However, factory production methods would also include "stressed skin" and "sandwich" forms of construction, (Appendix 4).

STRESSED-SKIN wall panels usually are made of framing members to which plywood skins are bonded either by glue-nailing techniques or adhesive application under heat and pressure. When the wall panel is loaded, both the framing members and the skin surfaces are stressed and act as an integral unit to carry loads. Since the plywood performs a structural function, the framing members ordinarily can be reduced in size, resulting in thinner wall sections. For example, wall and partition studs, which normally are 2" x 4", can be reduced to 1" x 3" or 2" x 3" with stressed-skin design. The technique is relatively common within the manufactured home industry.

SANDWICH PANELS have exterior and interior surfaces glued to and separated by lightweight core materials which generally are insulating. The panels are similar in principle to stressed-skin panels in that the surfaces become stressed and assist the core in resisting loads. A variety of materials are used in the construction of sandwich panels, such as polystyrene or urethane foam cores with aluminum, plywood or gypsum faces.

Stressed-skin and sandwich panel systems have exhibited excellent structural performance and provide many of the advantages of component fabrication. However, they may require careful design to incorporate mechanical equipment, may require special handling and erection procedures

Part 1

Platform Frame Construction

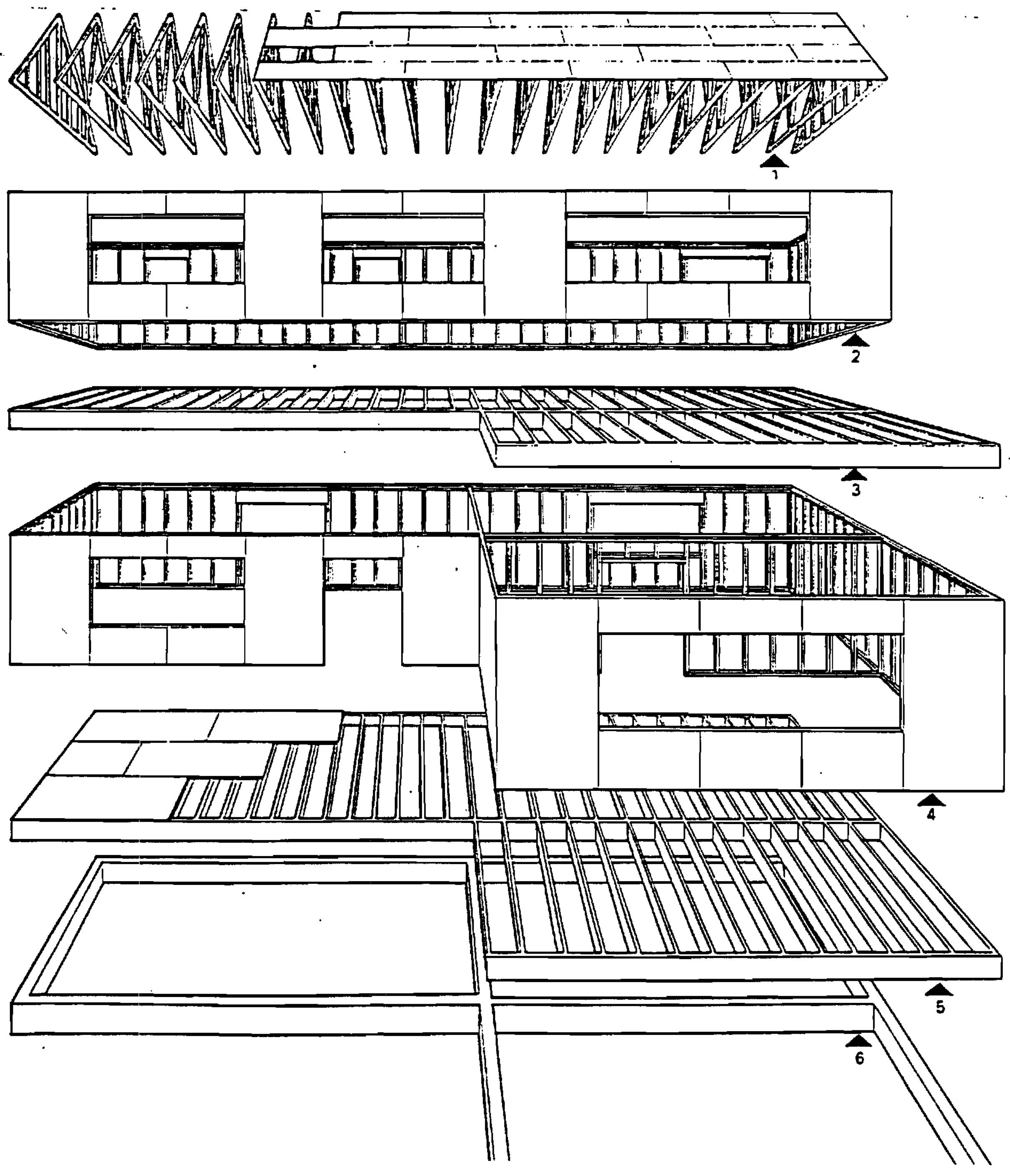
The term platform frame construction refers to that method of building with timber most widely practised in North America and now extensively used in the United Kingdom. Each floor extends to the outside edges of the building and provides a platform upon which exterior walls and interior partitions are raised in single storey height units.

To the designer the method offers complete freedom of layout and fenestration. For the on-site builder it provides at both ground and first-floor stages, a level working platform upon which to build his frames before tilting them into position. To the pre-fabricator it offers design scope and components of a size that can be easily transported and erected without mechanical aids. To the owner it offers a soundly built house free from the cracking of interior finishes. Any shrinkage that might affect finishes takes place in the joists where it can produce no side effects.

The structural recommendations made in this publication provide a guide to sound economic construction. Variations in methods and materials or unusual design features may well require the use of engineering calculations.

1. Roof framing
2. First floor wall framing
3. First floor framing
4. Ground floor wall framing
5. Ground floor framing
6. Foundations

Figure 2



in the field, and may not be acceptable to local codes. Therefore, they have had limited success to date with conventional construction.

Wall Insulation: Since the energy crisis of 1973 wall insulation has become a dominant feature of wall envelope technology. With conventional construction, a 3-1/2 inch insulation batt is typically installed between the studs, although loose-fill insulation can be blown into an open wall cavity. A 3-1/2 inch insulation batt usually has an insulation value of R-11, although R-13 batts are available. Adding 1/2 inch of insulated sheathing to the outside of the studs gives an additional R-3 to R-4, so the final R-value is about R-15.

Some builders use thicker insulated sheathing and R-13 batts to achieve R-19 in 2" x 4" walls. However, 2" x 4" construction has some drawbacks. For example, the 2" x 4" wall studs occupy about 20 percent of the total area of the wall. With an insulating value of only R-5 the 2" x 4" wall studs are poor insulators and form avenues called "thermal bridges" that allow heat to escape around the insulation. In addition, the relatively shallow stud depth does not allow adequate room to insulate behind plumbing and wiring the exterior walls. The end result is that 2" x 4" walls often have insulating values less than R-15.

Using 2" x 6" walls spaced 24 inches on centre alleviates some of the problems of 2" x 4" framing. The wider spacing allows fewer studs to be used, which helps offset the higher cost per stud and reduces the percentage of wall area taken up by framing, thus reducing heat losses due to thermal bridging. However, normal construction methods require an extra wall studs installed in boxed corners and partition wall intersections. These are not needed for structural support, but are used solely to provide a nailing base for interior and exterior finishing materials. With this form of construction, again potential "thermal bridging" is possible. In an attempt to overcome this problem, the extra studs may be replaced with drywall clips or nailer boards. These allow the insulation to extend into the corner and between the partition wall and sheathing.

It is recognized that placing thermal insulation on the outside face of a wall improves the thermal performance of the wall envelope - a "warm" wall is less likely to suffer problems of interstitial condensation. This has led to many stud-framed buildings being clad in a light rigid foam insulation material with an artificial stucco finish applied to the outer surface, (see later discussion). The latter gives suitable textural finish as well as adequate weather-resistance. Structural support to the building is achieved through the use of corner diagonal bracing, made of either wood or metal, let-in to the stud. Since let-in bracing combined with the rigid foam insulation can be less expensive than plywood, the material costs savings usually make up for any added labor costs. However, some builders are concerned about the stability of walls that use a non-structural sheathing on the outside face. For example, plywood sheathing, or other rigid board material, has been the conventional system used to provide lateral restraint at the corners to stud buildings. By modifying the traditional plywood sheathing design through the addition of a sandwich layer of rigid foam material applied between the plywood and the studs, a braced "warm" wall may be constructed, (Appendix 5).

Another problem of thermal bridging that may occur with some designs relates to the area of the headers over windows and doors. These can add up to 5 percent of the wall area. Standard headers for 2" x 4" walls are made by sandwiching 1/2 inch plywood between the framing lumber. In an attempt to reduce heat loss through the header, it is possible to form the header with a plywood center and use 1/2 inch rigid foam insulation. This construction detail doubles the R-value of the header and may cost less to install.

Interstitial condensation within stud walls may also be a problem with "cold-wall" construction. Whenever moist air comes into contact with a cooler surface, condensation is likely. Hence, in winter-time, any moisture vapor trapped within a stud wall that comes into contact with a cold surface is likely to condense, thus causing potential risk of decay within the wall, Appendix 6 (5) and Appendix 7 (6). The normal solution is to provide a vapor barrier, usually polyethylene, on the inside surface directly behind the drywall and to provide a layer of thermal insulation towards the outside face of the wall.

Exterior Insulation Systems: or EIS, involve placing insulation outside the structural frame to minimize thermal bridging and to protect the structure itself from thermal expansion and contraction. They were introduced to the United States in the late 1960s. Rising energy costs have contributed to a growing consumer demand for these products, estimated to command 10% of the walling market amongst dwellings, (see enclosed product guidebooks).

The major components of an exterior insulation system are the insulation and a protective coating of cementitious or acrylic veneer. The thickness of this coating may be as little as 1/32 inch and can be varied to meet the insulating needs of a building's climatic exposures while maintaining a uniform appearance on all facades. However, the early exterior insulation systems had problems with impact resistance, installation and quality control in general. The problem of impact damage to the veneer has been partially solved by reinforcing, but maintenance and security issues must still be addressed in the design process.

There are many climates where the placement of insulation on the exterior layer of the envelope does have significant energy conserving qualities, especially in combination with thermal mass. In the South-west, for example, thick masonry walls are used to retard the entry of heat during the day and delay its departure at night. Insulation placed on the exterior of a high mass wall traps heat leaving the building enhancing the wall's capacity to act as a heat sink and at the same time reducing infiltration. Colors may be chosen to absorb or reflect heat.

In addition, the ease with which the appearance of stucco is achieved contributes to its potential for visible integration. For example, veneer coatings are available in a wide range of colors and finishes. Exterior insulation systems can be used over almost any substrate, and are well suited to retrofit work. Their use can greatly simplify detailing; they can meet glass without a frame, do not require expansion members and can cover dissimilar materials for a uniform appearance. Exterior insulation systems have also been used in historic preservation work to mimic the appearance of carved stone, terracotta and other building materials that are no longer available or are difficult to obtain.

Theoretically, the veneer coating can be applied to any shape that the substrate assumes. The continuity of the protective coating can be used as a thermal shield over projecting elements, such as chimneys, as well as on planar surfaces. It can also be used on slopes greater than 45 degrees. The common uses of these systems seem to follow the more traditional profile customarily seen with stucco or precast concrete walls.

There are two general types of veneer coatings available. These ar the acrylic polymer-based coatings, or PB, and the Polymer-modified portland cement coatings, or PM. Acrylic coatings are very flexible and can be applied in very thin coats. They usually come ready-mixed from the factory and hence their color consistency is good. They have less impact resistance than cementitious coatings, however, and usually require reinforcement. Cementitious coatings are more rigid and require a thicker application. While some products use only an acrylic veneer, most are a combination of a cementitious base coat and an acrylic finish coat.

Most manufacturers will mix custom colors in addition to those featured in their color chart. The available hand-trowelled or machine-applied finishes include a complete range of standard stucco finishes as well as ones that imitate limestone, corrugated concrete and exposed aggregate concrete.

The problem of impact damage to the veneer has been partly solved by reinforcing. The base and veneer coatings can be reinforced with wire mesh, although most manufacturers prefer a glass fibre fabric. Some coatings include chopped glass fibers in the matrix that act as internal reinforcing. Nevertheless, protection from predictable impact sources need to be considered in the design, as well as the possibility of intentional penetration by intruders.

Expanded polystyrene (EPS) or bed board is by far the most commonly used insulation. Other types have been used successfully, but expanded polystyrene is preferred because of its low cost. All types of rigid insulation now used with EIS are flammable. Some fiberglass insulation manufacturers are investigating the possibility of marketing a system that incorporates rigid glass fibre insulation, which would improve the fire safety characteristics.

Exterior insulation systems resist fading, can be readily repaired and are easily re-applied as future needs dictate. One manufacturer has recently marketed a re-coating veneer.

Exterior insulation systems may be installed as prefabricated panels, or the veneer may be field-applied. Application of the veneer is relatively economical; the veneer can be applied quickly and the procedure is not technically complex. There is some controversy about the proper method for connecting the insulation to the substrate, especially when gypsum sheathing is used. Some manufacturers use mechanical fasteners while others use a liquid adhesive. The Gypsum Association objects to the use of adhesives alone to attach to a gypsum sheathing substrate; they claim that the sheathing paper face is not structural and is asphalt-impregnated so that delamination can easily occur. Most manufacturers will use mechanical fasteners if required to do so.

One of the principal advantages of exterior insulation systems is their ability to provide thermal and moisture protection without placing a heavy dead-load burden on the structure. When the system is supported by light gauge metal framing, however, the architect must determine the proper allowable deflection of the frame. Most manufacturers recommend L/240 as a proper allowable deflection, but other elements of the building, such as windows where the exterior insulation system is used as a spandrel, should be considered.

All current building codes contain restrictions on exterior insulation systems. Some cities have prohibited their use, while other cities review it on a case-by-case basis. The principal difficulty is that both the veneer coating and the plastic insulation are flammable and emit toxic gases when burned.

<u>AIRTIGHT DRYWALL</u>: The Airtight Drywall Approach (ADA) technology also offers potential for greater efficiency in the use of buildings. ADA is an air barrier system that connects the interior finish of drywall and other building materials together to form a continuous barrier. ADA has been used on hundreds of houses and has proven to be an effective technique for reducing infiltration as well as keeping moisture, dust and insects from entering the home (7).

In a typical drywall installation, most of the seams are sealed by tape and joint compound. However, air can leak in or out of the home in the following locations:

* Between the edges of the drywall and the top and bottom plates of exterior walls.
* From inside the attic down between the framing and drywall of partition walls.
* Between the window and door frames and drywall.
* Through openings in the drywall for utilities and other services.

ADA uses either caulk or gaskets to seal these areas and make the drywall a continuous air barrier system.

<u>ADA advantages</u>: Effective - ADA has proven to be a reliable air barrier; simple - does not require specialized subcontractors or unusual construction techniques. If gasket materials are not available locally, they can be shipped easily; does not cover framing - the use of ADA does not prevent the drywall from being glued to the face of wall studs and ceiling joists; scheduling - gaskets can be installed any time between when the house is 'dried-in' and the drywall is attached

to framing; some caulks remain pliable and can also be applied several days before the drywall is installed; adaptable - builders can adapt ADA principles to suit any design and varying constructions schedules; cost - materials and labor for standard designs should only cost a few hundred dollars.

ADA Disadvantages: New - although ADA is a proven technique, many professionals and code officials are not familiar with its use; not a vapor barrier - if required, a separate vapor barrier must be used with ADA. However, faced insulation batts, polyethylene plastic, or vapor barrier paint work well; requires thought - while ADA is simple, unusual construction designs and techniques require careful planning to ensure that the air barrier remains continuous. However, ADA is often the most error-free and reliable air barrier for unique designs; requires care - gaskets and caulking can be damaged by subcontractors when installing the drywall or utilities.

ADA Techniques: Exterior Walls

* Install gaskets or caulk at the top and bottom plates of exterior walls so that when drywall is installed it compresses sealant to form an airtight seal against framing.

* Use drywall joint compound or caulk to seal the seam between drywall and electrical boxes. Install gaskets behind cover-plates.

* Provide for vapor barrier by using faced insulation batts, polyethylene, foil-backed drywall or vapor barrier paint.

* Seal between the bottom plate and sub-flooring.

* Seal penetrations through the top and bottom plates for plumbing, wiring and ducts.

Partition Walls

* Seal the drywall at either the top or bottom plate of partition walls. If sealing at the bottom plate, then also seal around interior door frames.

* Seal the duct work at the intersection of partition and exterior walls.

* Seal penetrations through the top and bottom plates for plumbing, wiring and ducts.

Polyethylene Air Barrier: Polyethylene is frequently used as a vapor barrier in energy efficient homes, and when installed correctly can also serve as an effective air barrier. To stop air leakage, the polyethylene (poly) must be sealed to the framing, and all penetrations and seams in the poly sealed as well. In practice, it is difficult to install poly in an airtight manner. Hence for most houses, the poly serves as only a vapor barrier - not an air barrier.

Polyethylene external installation include: (i) staple Poly at 6-inch intervals to the interior surface of the wall studs and plates after all utilities are roughed in and insulation is installed; (ii) overlap the ends of separate sheets at lest six inches, staple the sheets over a framing member, and caulk or tape the seam; (iii) caulk or tape poly to electrical boxes, plumbing and registers; (iv) pleat the poly at the corners so that drywall can fit tightly.

An exterior air infiltration barrier, or house-wrap, helps reduce air leakage through outside walls. Most products block only air leakage, not vapor diffusion, so they are not vapor barriers. Most products are sheet materials that are stapled and sealed to the wall between the sheathing and exterior finish material. Common brands include Tyvek (TM), Barricade (TM) and Airtight-Wrap (TM).

A house-wrap must be sealed with caulk or tape at the top and bottom of the wall and around any openings, such as for windows, doors and utility penetrations. A house-wrap can help reduce infiltration through exterior walls, but by itself it is not a continuous air barrier for the entire envelope and hence not a substitute for the ADA or poly systems. One alternative to a house-wrap is to use the exterior sheathing as an infiltration barrier.

Exterior Finishes on Plywood Composite Panels

Plywood siding is a durable exterior structural product which currently accounts for about 25% of all the siding area on new residential buildings, (Appendix 8). Although some plywood siding is pre-finished and some is left unfinished and allowed to weather naturally, most of it is finished at the job site with various trade-sales finishes.

Finishes are used to protect the wood and achieve various aesthetic effects. Because of the unique nature of wood, a wide variety of finishing systems are used. Semi-transparent stain finishes are designed to emphasize the grain-figure and texture characteristics of the siding; whereas the purpose of solid-color stains is to hide the grain and color of the wood while letting the texture show. Two- and three-coat house paints form a highly durable coating, in addition to hiding the grain and de-emphasizing texture to some degree.

Many consumer complaints about plywood siding have been traced to poor-quality finishes or improper application techniques. At the present time, no reliable basis for judging finish quality exists. The history of the performance of a manufacturer's product line is not a reliable guide to quality because the manufacturer may periodically modify formulations as a result of changes in price and availability of various raw materials, or as new raw materials become available. Too often, the selection of the finish to be used on plywood siding is based on cost rather than on quality, and this procedure often results in unsatisfactory performance. A recent study by the American Plywood Association (8) has found that hot, humid conditions lead to greater and quicker breakdown of applied finishes and paints although not all equivalent materials degraded in identical ways.

MASONRY WALLS

A masonry wall assembly is a good example of the adage "*the whole is equal to the sum of its parts*", i.e. the masonry units, the mortar that bonds them together, and the workmanship of the mason all influence the eventual performance of the finished wall. Hence, the use of quality materials will not compensate for poor workmanship, nor will masonry constructed with the finest workmanship give satisfactory performance if poor materials are used. Above all, the wall must be properly designed for the necessary strength, water-tightness and duarability. In addition, depending on the walls location and use other wall properties could be equally important, e.g. resistance to heat transfer, fire resistance, sound resistance and radiation protection.

Past experience and observation of the performance of masonry walls has resulted in the development of certain standards and minimum requirements governing their design, e.g. the American National Standards Institute (ANSI) Building Cost Requirements for Masonry ANSI A41.1 -1953 (R 1970); and American Concrete Institute (ACI) Building Code Requirements for Concrete Masonry Structures, ACI Standard 531-79

Load-bearing and non-load-bearing masonry walls may be constructed of clay and/or concrete masonry units (CMU). They are classed as solid walls, cavity walls, veneered walls and reinforced walls, depending on methods of construction.

In solid, cavity and reinforced masonry systems, the installation of insulation and mechanical equipment may be incorporated between thicknesses of masonry or within furred spaces on the interior side of the wall.

Usually, masonry walls are left exposed, but they may be finished on the exterior with stucco or other coatings. Interior surfaces can be finished with applications such as plaster or drywall or can be left unfinished as the desired appearance.

A masonry wall assembly should be suitable for the conditions of loading, the locality, the exposure and the type of occupancy. In many areas, single-thickness masonry walls are adequate for the control of heat and moisture and may be more economical than wood stud walls. Generally, however, the selection of masonry construction is based on functional performance and desired appearance.

WALL TYPES

No one wall assembly is suitable as a standard design for all exposures, conditions of loading or appropriate to all localities and types of occupancy.

Solid Walls: A solid wall acts as a unit to support loads and is built up of units laid close together with all joints between units filled solidly with mortar. Solid walls may be built of either solid or hollow masonry units (or both in combination) in any required thickness, and are used for either load-bearing or non-load-bearing construction.

Solid walls may be further classified depending on the type of units used in their construction. They may consist of: (1) solid units of brick or concrete brick and block; (2) hollow units of concrete block, hollow brick or structural clay tile and (3) composite (faced) walls consisting of facing and backup units of different materials bonded so that both facing and backup are load bearing.

All nationally recognized building codes permit the use of exterior load-bearing 6" masonry walls for one-story, single-family dwellings where the wall height does not exceed 9' to the eaves and 15' to the peak of the gable.

However, external walls made of solid brickwork should only be constructed when investigation has shown that heavy rain and wind as well as the directional alignment of the building will not cause problems. It is recommended that where normal rain pressure the following should be observed:

* The wall thickness should not be less than 15" (375mm)

* Brick and mortar material must be matched for their absorbency and capillary capacity.

* External and internal brickwork should consist of bricks of equal absorbency, strength and capillary capacity.

* All mortar joints - especially the bonded 3/4" (20mm) thick joints within the brickwork - must be free from cavities.

* Brick and mortar materials should permit free vapor diffusion.

If their appearance and character are not to be sacrificed, external walls made of solid brickwork and concrete, which have to satisfy demands regarding surface temperature, surface condensation, comfort and energy saving, must be selected with either economically additional insulating measures on the inside or other types of construction, such as cavity brickwork or solid concrete with core insulation. The thermal insulation value of the whole wall cross-section should not be below the value specified in the local codes. Internally applied thermal insulation layers should either be protected by a vapor barrier applied inside the room, if they are made of a vapor permeable material (e.g. mineral fibre slabs), or have a high thermal insulation value in themselves. In addition, solid wall constructions with an internal thermal insulation layer, especially those with core insulation, may require adequate expansion joints.

Cavity Walls: A cavity wall is built up of solid or hollow masonry units which are deliberately separated into an inner and an outer wall. A cavity wall consists of two wythes of masonry at least 4" thick separated by a continuous air space not less than 2" or more than 4-1/2" wide, bonded together with metal ties or joint reinforcement. The exterior wythe may be brick or hollow brick. The interior wythe may be brick, hollow brick, structural clay tile, solid or hollow concrete masonry units.

The cavity offers two advantages in areas of severe exposure. The continuous air space (1) provides insulation value to the wall and permits insulation to be installed within the wall to further reduce heat transfer, acts as a barrier to moisture, eliminating any need for furring, since rain penetration to the interior is practically impossible if proper flashing and weep holes are installed.

The cavity must be kept free of mortar dropping that could form a bridge allowing moisture to penetrate to the interior face. Weep holes must be provided in conjunction with flashing to properly drain the cavity of any water that may enter the exterior.

A vapor barrier is not required in a cavity wall where: (1) the cavity is insulated with fill materials such as water repellent vermiculite or silicon treated perlite, which will not retain excessive moisture; or (2) rigid board materials, such as glass fibre, foamed glass or foamed plastics, that are at least 1" less in thickness than the cavity and are installed next to the inner wythe.

Veneered Walls: The use of masonry units only as a facing material (veneer), without utilizing its load-bearing properties, is common in residential construction. The facing of a veneered wall is attached but not bonded to act structurally with the load-bearing backup material.

Brick veneer walls carry only their own weight. Therefore Type N mortar is recommended, a mortar consistent with the principle that the lowest strength mortar be used compatible with structural requirements.

In wood frame construction the brick veneer is anchored to the back-up wall by nailing corrosion-resistant corrugated metal ties to wall framing members. In metal stud wall construction the veneer is anchored using adjustable wire ties, screwed to the metal studs. The ties, spaced not to exceed 16" horizontally and 24" vertically, permit vertical and horizontal movement parallel to the plane of the wall, but resist tension and compression perpendicular to the plane of the wall.

STRENGTH & STABILITY

Under average conditions of exposure and loading, the minimum requirements of the American National Standards Institute (ANSI), Building Code Requirements of Masonry, (ANSI A41.1-1953) (R 1970) and the American Concrete Institute (ACI), Building Code Requirements for Concrete Masonry Structures, (ACI Standard 531-79) are recommended as the basis for wall design. The requirements for wall thicknesses and the provisions for unsupported wall heights and wall lengths have developed from performance records over a long time and are incorporated in most up-to-date building codes.

Compressive Strength: The ultimate compressive strength (strength at failure) of masonry walls is closely related to the compressive strength both of the masonry units and the mortar; quality of workmanship; the thickness of the mortar joints; the regularity of the units' bearing surfaces; and the workability of mortar.

The principal loads producing compressive stresses in walls are the dead loads, i.e. the combined weight of the walls, floors and roofs; and the live, i.e. combined weight of the occupants, furniture and equipment.

Typical construction today does not require walls to carry large vertical loads. About 75% of the brick produced today has compressive strengths of over 4500 psi; concrete block, over 1000 psi. When used with typical mortars having compressive strengths in the range of 750 to 2500 psi, it is evident that most masonry walls for one-story buildings have far more compressive strength than is needed.

Tests have established the relationship between the compressive strength of walls and masonry units from which they are laid, e.g. the compressive strength of walls constructed of hollow concrete units, laid with face-shell mortar bedding, is approximately 42% of the compressive strength of the units, and 53% when laid with full mortar bedding.

Transverse Strength: The transverse strength of a wall is a measure of its lateral stability; that is, its resistance to such lateral forces as wind pressure, earth pressure (in foundation or retaining walls), and earthquake forces. Transverse loads induce tensile stresses in the masonry that must be resisted. The lateral stability of masonry walls depends on the tensile strength of bond between mortar and units. Factors that will increase tensile strength will also increase transverse strength. These include: (1) the use of Type S mortar mixed with the maximum amount of water consistent with workability; (2) maintaining the suction of clay masonry units below 20 grams per minute, per 30 s. in.; and (3) using good workmanship in which mortar joints are full.

Lateral Support of Walls: Masonry walls must be laterally supported or braced at certain intervals either by vertical or horizontal supports. When the limiting distance is length, vertical supports may be columns, pilasters or cross walls. When the limiting distance is height, horizontal supports may be floors, beams or roofs.

Lateral Support During Construction: Masonry walls are usually not designed to be freestanding, that is without support from columns, piers or cross-walls. Wind pressures can create four times as much bending stress in a new freestanding wall as in a wall which is connected to other structural elements of the building. This stress often occurs at the bottom of the wall where flashing and lack of bond in fresh mortar decreases the wall strength to resist tensile wind forces.

Bonding and Anchorage: Two methods are generally used in the structural bonding of wall assemblies. One method, using masonry bonders, is accomplished by overlapping and interlocking the masonry units. The other, and the preferred method, is the use of metal ties imbedded in connecting mortar joints. The masonry bonded wall is based on variations of two traditional methods of bonding: (1) English bond, consisting of alternating courses of headers and stretchers, and (2) Flemish bond, consisting of alternating headers and stretchers in every course. The usual requirements for bonding metal tied walls are 3/16" diameter steel ties (or metal ties of equivalent stiffness and strength) spaced so that at least one tie occurs for every 4-1/2 sqft of wall area. The maximum vertical distance between ties should not exceed 18" and the maximum horizontal distance should not exceed 36". Ties in alternate courses should be staggered.

Rain penetration in an 8" masonry bonded wall may be the result of several factors: (1) It is sometimes difficult for the mason to obtain full mortar joints between brick headers, and moisture may be conveyed to the inside face of the wall since the header is continuous through the full wall thickness; (2) It is difficult to bond brick and larger, heavier backup units without impairing the bond between headers and mortar. If the backup unit is set on the header before the mortar has time to stiffen, the head brick will settle unevenly and a crack may develop. The differences in thermal and moisture expansion coefficients of facing and backup materials may also affect the weather-tightness of the wall. The differences are normally greatest between brick and concrete block where movement of the concrete block backup, due to drying shrinkage, creates an eccentric load on the brick header which tends to rupture the bond between headers and mortar at the external face.

For these reasons, cavity walls or solid metal tied walls are recommended, particularly where resistance to rain penetration is important or where wide variations in the physical characteristics of facing and backup materials exist.
Concrete Block Load-bearing Walls: When such walls intersect they should not be tied together in a masonry bond, except at the corners. One wall should terminate at the face of the other wall with a control joint located at this point. For lateral support, bearing walls are tied together with a metal tie bar 1/4" thick, 1-1/4" wide and 28" long, with 2" right angle bends on each end. Tie bars are spaced not over 4' apart vertically. The bends at the ends of the tie bars are embedded in cores filled with mortar.

Concrete Block Non-Load-bearing Walls: Such walls are tied to other intersecting walls using strips of metal lath or 1/4" mesh galvanized hardware cloth placed across the joint between the two walls. The metal strips are placed in alternate courses in the wall. When one wall is constructed first, the metal strips are built into the wall and later tied into the mortar joint of the second wall. Where the two walls meet, a control joint should be provided if the joint is exposed to view.

Reinforced Masonry Walls: These walls are structurally bonded by grout which is poured into the cavity (collar joint) between the wythes of masonry. The grout core also serves to contain and bond the reinforcing steel.

MOISTURE CONTROL

The principal sources of moisture in masonry are rain penetration, capillary action from contact with the ground and condensation of vapor within the masonry.

Methods used to control rain penetration in masonry walls include adequate flashing, tooled mortar joints, parging, painting, tightly caulked door and window openings, sufficient slope (wash) to readily drain all horizontal surfaces (as at sills and copings, including an overhang and drip) and adequate gutters and downspouts.

Condensation of water vapor may occur within uninsulated masonry and can be controlled by installing a vapor barrier on the warm side of the wall.

Weep Holes : Flashing should drain to the outside and should be provided every 24" horizontally in the head joint immediately above any flashing. It is recommended that "wicks" made of 1/4" glass fiber rope or similar inorganic material be placed in the weep holes, or 1.2" glass fiber insulation can be placed in open head joints. When weep holes are filled with inorganic materials they should be spaced every 16".

Flashing Installation: Masonry must be relatively smooth and free of projections that might puncture flashing and destroy its effectiveness. Through-wall flashing should be placed on a thin bed of mortar with another thin mortar bed placed on top of the flashing to receive and bond the next masonry course. Flashing seams must be thoroughly bonded to prevent water penetration.

Flashing Materials: Because replacement costs can exceed the initial installed costs, it is prudent to select a permanent flashing material.

Copper: It is not materially affected by the caustic alkalis present in masonry mortars, hence copper can safely be imbedded in fresh mortar and will not deteriorate in continuously saturated, hardened mortar unless excessive chlorides are present. Galvanized Steel and Lead: Subject to corrosion in fresh mortar and when placed in contact with mortar. Aluminum: Subject to attack by the caustic alkalis present in fresh, unhardened mortar. Stainless Steel: Stainless steel flashing are available - durable, highly resistant to corrosion, excellent moisture barriers and are surprisingly workable. Bituminous Fabrics: Flashing materials composed of fabrics saturated with bitumen are used as damp checks and as low cost substitutes for metal flashing at the base of walls, heads of openings and at window sills. Not as permanent as metal flashing. Plastics: Plastic flashing are available that are tough, resilient and highly resistant to corrosion. Some plastic flashing will not withstand the corrosive effects of masonry mortars and recognized standards have not yet been established for plastic flashing.

Wall Strength: Limited test data indicate that where mortar is placed immediately above and below copper flashing, flexural strength is about 30% to 70% of non-flashed walls.

Caulking Joints: Mortar joints between the masonry and the perimeter of exterior door and window frames, at control joints, and the joints around all other wall openings required to be weather-tight should be cleaned out to a uniform depth of at least 3/4".

Rendering and Stucco

For many single skin brick walls the use of rendering is the most economic form of external cladding. Even the highly insulated materials for wall construction that are frequently used today (e.g. light-weight insulating blocks) need protection against rainwater, as they can easily become saturated because of the nature of the material and its high absorbency. Extensive investigations have long since proved that satisfactory rendering is able to offer effective protection against heavy rain.

A great number of different types of rendering - from simple hydrated lime mortar to high-grade factory prepared rendering or rendering treated with water-repellent substances - is available and can be used to suit the climatic demands. A dense surface, free of defects, an absorbency as low as possible combined with vapor permeability, are required for the effective functioning of all rendering.

As external rendering represents a relatively thin and brittle material skin, damage is almost exclusively in the form of cracks and other structural failures. Damp defects show up mainly as a consequence of such failures and defects. The great frequency of these rendering defects can be attributed to the number of factors affecting rendering quality and stress.

The right type of rendering and its correct composition must be selected for very different wall materials to be finished. High demands are put on the quality of the base (uniformity of material, evenness, sealed joint, rigidity); the method of application from the mixing of mortar to the subsequent treatment of the rendering conceal many sources of defects; the climatic demands are many and great.

1. External rendering must be applied at least 3/4" (20mm) thick. The one coat (in the case of light weight mortar) or two coats (in the case of normal mortar) layer of rendering must have a fall in strength in the base from inside to outside.

2. For walls exposed to heavy rain, water-repellent or at least water-proof rendering is preferable; it must allow an adequate exchange of water vapor between the wall section and the outside air, however. This can be achieved through suitable water-repellent mortar additives in the outer rendering or by appropriate external coating. The hardening of the rendering must not be affected by the inclusion of water-repellents.

3. Rendering should also be applied only on a firm base with sealed joints. Dry, clean bases should be wetted first, smooth or very absorbent bases should be sprayed with a coarse rendering at least 12 hours before the start of rendering.

4. If an additional thermal insulation layer is necessary on walls with external rendering, it should be placed on the inside or within the wall section. Damp-proof thermal insulation material with a high resistance to vapor diffusion (e.g. polystyrol hard foam slabs), or in the case of vapor permeable insulating material (e.g. mineral fibre slabs) an internal vapor barrier (e.g. coated aluminum foil), should be used.

5. For solid slab rendered wall sections, which are to be constructed without additional thermal insulation layers, a thermal insulation value which lies considerably above the minimum value should be aimed by selecting suitable structural materials for the wall. Wall construction methods should not be used if they cannot reach the thermal insulation value of 1.0m^2K/W, which can be achieved with light weight blocks 1' (300mm) or aerated concrete 10" (250mm).

6. Rendering should, if possible, have a moderately rough surface; textured rendered surfaces help to reduce the affect of surface discoloration and wash-staining.

7. Scaffolding should be set up in front of the wall at a distance of 1' (300mm) and be anchored so that no subsequent work is necessary on the rendered wall surface. The work should be divided up in such a way that related surfaces can be finished without disruption to work. If possible rendering should not be carried out in direct sunlight and strong wind; in any case the freshly rendered surfaces should be protected by tarpaulins or be kept damp during setting.

8. Where there is a change in base material, along the junction of different materials, and where there are connections to other structural elements, as well as over expansion joints in the base, the rendering should have a carefully sealed joint. Small areas of the base which cannot be rendered (ends of joists) can be bridged with galvanized mesh with at least 4" (m) lateral overlap.

Parging and Damp-proofing: Where subsoil conditions do not cause water to build up hydrostatic pressure against masonry foundation walls below grade, moisture penetration can be controlled by parging and damp-proofing (coatings applied to resist moisture penetration due to capillarity). Type M mortar parging is applied to the exterior face of the wall below grade and trowelled to a smooth, dense surface extending from the footing to 6" above finished grade. Coal tar or asphalt-based damp-proofing products may be applied over parging to increase resistance to moisture penetration.

In well drained soils, one of three methods may be used: (1) parging alone may be applied in two 1/4" thick coats of mortar; (2) one 1/4" coat of parging followed by two brush coats of bituminous damp-proofing; or (3) one heavy trowelled-on coat of cold, fiber reinforced asphaltic mastic applied directly the masonry surface. In wet and impermeable soils, moisture control can be achieved either by (1) two 1/4" thick coats of mortar plus two brush coats of bituminous damp-proofing or (2) one 1/4" thick mortar application followed by one heavy trowelled-on coat of cold, fiber-reinforced asphalt mastic. Parging should be moist cured for at least 48 hours and dry before damp-proofing is applied.

Painting Masonry: Masonry paints are of four general classifications, (1) cement-based paints which come in powdered form and are mixed with water before applying; (2) water-thinned emulsion paints which include butadiene-styrene, vinyl acrylic, alkyd and multi-colored lacquers; (3) fill coats which are similar to cement-based paints but contain an emulsion paint in place of some water, giving improved adhesion and tougher film than unmodified cement paints; and (4) solvent-thinned paints which, except for special-purpose paints and special applications, should only be used on interior masonry walls.

INVESTIGATING MASONRY FAILURES

Masonry walls, although capable of carrying loads, are frequently designed to provide water-and air-tight envelopes only. As a result, their diminished function has resulted in relatively thinner walls. While earlier thicker walls served as reliable water dams, today's thinner walls depend on mortar joints as a critical element for their integrity. Hence, any cracking within the mortar bed may result in moisture passing from the outside face of the brick veneer to the inside face. In addition, to make matters worse, these thinner walls serve unintentionally as rigid membranes that attract high membrane, in-plane forces. Incapable of resisting such loads, these walls will often crack, spall and thus fail to provide a reliable protective envelope against water and wind gusts.

Newly developed methods to correct this condition entail either separating the masonry enclosure from the structural frame by introducing both horizontal and vertical movement joints (often referred to as "soft" joints); or using so-called "drainable walls" such as the popular two-wythe interior cavity type walls that are drained by weep holes. Since these walls contain so many components, enormous care in construction and the highest level of quality control are required to reduce the high probability of failure.

The most common forms of masonry failures are:

* Instability
* Fracture-cracks, splitting, mortar separations, spall, shaling etc.
* Failure of connections, anchors, and support system by corrosion, pull-outs, fracture, deflections, adhesive separations etc.
* Water penetration through wall joints and the wall base material.
* Lack of temporary bracing during construction.

* Inappropriate mortar specification.

* Poor workmanship during construction.

* Excessive compression loading on brick veneers with high slenderness ratio (height/width) and inappropriate or insufficient top anchors.

In addition, construction defects such as overhanging shelf angles at corners of buildings, missing shelf angles, brick units overhanging shelf angles and an inadequate number of anchors, short anchors, or totally missing anchors just accelerate such failures.

The stability of masonry walls is often further compromised when "soft joints" are constructed with mortar to actually yield "hard joints". In such cases, the result is local wall buckling. With exposed concrete slabs ("eyebrows") hard joints can spall brick and concrete. If "soft" joints are not continuous, cracks will develop at the demarcation line between "soft" (compressible) and "hard" (rigid) joints.

<u>Spall, cracks and mortar separations</u>: Walls constructed of brick, block or natural stone will fail when stressed beyond their tensile and compressive strength. Stress is caused by one or more or a combination of the following:

* Foundation movements

* Wind and earthquake movements

* Shortening of the structural frame (elastic, creep, shrinkage)

* Expansion of the masonry (water absorption, temperature, insufficient baking).

The first and most important step in masonry maintenance or repair is, therefore, recognizing that a problem exists. Inspections can be performed either independently, without benefit of past inspection records, or progressively, to establish change in previously noted problem ares. Visual examinations are normally adequate to identify areas that may require more detailed inspection.

To determine deterioration in masonry units look primarily for weathering (freezing and thawing) damage as evidenced by surface erosion, cracks, spalled surfaces of unit and mortar combined. Extremely soft units (common brick) as well as extremely hard units (glazed brick) are both highly susceptible. Spalling is especially evident in older structures where masonry is severely exposed. Masonry is vulnerable at or below grade, in unheated buildings, in parapet walls, retaining walls, planters, wing walls, etc. Long-term leaky walls should also be checked. Isolated spalling of units at shelf angles could indicate a critical structural problem.

It is also necessary to check masonry in caps and sills and immediately below coping, caps, and sills that do not have overhangs, drips and flashings. Masonry below projections, recesses, or in other ornamentation without permanent wash surfaces or flashing coverings should also be checked. This applies to both units as well as mortar. Snow melted in a wall can also lead to serious freeze/thaw deterioration. For example, during winter periods, snow and ice can build up, primarily on horizontal surfaces. On a sunny day, the heat will melt a portion of the snow or ice. The moisture will then penetrate the wall system, converting to ice when reaching a cold surface in the shade. Moisture entering ornamentation during any season will eventually penetrate the exterior masonry or even the interior of the building. When confined, water freezes, expanding with pressure up to 15,000 psi.

Evidence of brickwork deterioration may be evidenced at the mortar joints in exterior masonry. A scratch hardness test of the mortar joint surfaces can establish mortar soundness or deterioration. Visually, deteriorated mortar expands outward or upward, dislodging overlaying courses.

With defective mortar joints, tuckpointing is suggested to mask grout or rebuild the masonry. Some leaky walls with raked joints are ideally suited to mask grouting: Tuckpointing, which involves removing deteriorated surface mortar to a depth of approximately 3/4 inch, may be the best option. Tuckpointing mortars should be pre-hydrated - untouched for one hour after initial mixing - to minimize shrinkage.

Tuckpointing mortar mixes (proportions refer to portland cement, lime, and sand, by volume) should be no stronger than existing mortar for typical exterior walls. Use the following as a guide:

* Before 1900: 1:3:12 (Type K)

* Soft brick or stone:1:2:9 (Type O)

* Intermediate or hard materials: 1:1:6 (Type N)

* Horizontal surfaces: 1:1/2:4.1/2 (Type S)

* Drainage mortar: special 1:0:5 mix, with the aggregate a concrete rather than masonry sand.

The interface between unit and mortar (top of mortar/bottom of unit, especially) can experience extensive loss of bond, normally recognizable as a slight opening similar to a crack. This loss can be caused by the use of hard, low-suction masonry units; high cement content mortars; or an incompatible unit/mortar combination. A bond can also be damaged by a "typical" acid wash, which may be more harmful than long-term weathering.

Since mortar joints are so vulnerable, every effort must be made to obtain a tight joint:

* Quality joint tooling

* High bond strength at the interface between the mortar and the brick or stone units

* Increased mortar density and resistance to water permeability.

<u>Crack Control</u>: All walling materials move due to (1) expansion or contraction of the masonry due to temperature changes; (2) expansion or contraction due to changes in moisture content of units - particularly concrete masonry units; (3) contraction in concrete masonry units due to chemical reactions called carbonation; (4) structural movements caused by unequal settlement of the foundation or at the point of concentration of applied loads; (5) concentration of stress that develops at wall sections where door, window and other openings occur and (6) members built into the wall that locally restrain or prevent the wall from moving, as at the junction of floors, roofs, columns and intersecting walls, table 1.

<u>Expansion joints for clay masonry</u>: A clay masonry wall 100' long might expand approximately 3/8" due to a temperature increase of 100 deg. F. Expansion joints are installed to provide a complete separation through the structure. They are expensive, may be difficult to maintain and should be avoided if possible.

Cracking due to shrinkage can be controlled by one or more methods: (1) moisture controlled, Type I concrete masonry units manufactured according to ASTM specifications to reduce shrinkage potential; (2) horizontal steel reinforcement to increase tensile resistance to cracking and to minimize the width of cracks and (3) control joints located to accommodate wall movements. When stucco or plaster are applied directly to masonry units, control joints should extend through the stucco or plaster. Control joints are not recommended for basement or foundation walls.

Failures from stress that result in cracking are difficult to assess visually. However, the Building Research Establishment in the U.K. have issued a rule-of-thumb guide that enables an initial inspection to determine the need for repair work (9):

Category 0: Hairline cracks less than 0.1mm width. Degree of damage: Negligible.

Table 1—Movements that may affect cladding

Cause	Effect	Duration, frequency	Examples of materials or components affected	Significance for design
1 Temperature changes	Expansion and contraction	Intermittent, diurnal, seasonal	All. Where restrained, distortion or damage may occur. Distortion may also result from temperature gradients or from from non-homogeneity	Extent of movement is influenced by thermal coefficient, exposure, colour, thermal capacity, insulation provided by backing
2 Moisture content changes: a) Initial moisture absorption	Irreversible expansion	Relatively short term, due to absorbtion of moisture after manufacture	Brick and other ceramic products	Depends on age of product most movement occurs within first 3 months of product's life
b) Initial moisture release	Irreversible contraction	Relatively short term	Mortar, concrete, sand-lime bricks	May require measures to control or distribute cracking
c) Alternate absorption release of moisture in service	Expansion and contraction	Periodic—e.g. seasonal	Most porous building materials, including cement based and wood or wood based products. Restraints, humidity gradients or non-homogeneity may produce distortion. Laminates of dissimilar materials may bow particularly if their construction is asymmetrical	Generally less significant for cladding than are thermal movements but wood experiences large moisture induced movements across the grain.
3 Loading on structure: a) Elastic deformation under service loads	Normally insignificant in vertical members but horizontal members may deflect	Continuous or intermittent under live loads; long term under dead loads	Suspended floor and roof slabs, beams, edge beams or spandrels, of all materials (whether they support or "contain" the cladding)	Needs consideration in relation to fixings and bearings for cladding and to possible compression of "contained" cladding; deflections in pre-stressed concrete members may be relatively large
Creep	Contraction of vertical and deflection of horizontal members	Long term	Reinforced and pre-stressed concrete components as above	Needs consideration as above. May also be significant where load bearing concrete walls or columns have cladding such as mosaic or other tiling directly bonded
4 Wind loading on cladding	Deflection	Intermittent	Lightweight cladding, including fixed and opening glazing; sheet siding	Extent of deflection depends on exposure for a given stiffness. Deflection is commonly designed not to exceed 1/240 of the span in order to avoid damage to sealants or glazing
5 Chemical changes; a) Corrosion	Expansion	Continuous	Iron and other ferrous metals	Depends on protection or on corrosion resistance of material; electrolytic corrosion may require consideration. Corroding fixings can seriously disrupt cladding
b) Sulphate attack	Expansion	Continuous	Portland cement based products in construction where soluble sulphate salts (e.g. from high-sulphate bricks) and persistent dampness present	Significant for cladding where the construction affected has cladding such as mosaic or other tiling or rendering, bonded directly to it
c) Carbonation	Contraction	Continuous	Porous Portland cement products, such as concrete, lightweight concrete, asbestos-cement	Not very significant unless distortion might result—for example, asbestos cement sheets painted on one face only
6 Vibration (from traffic, machinery, wind forces)	Generation of noise, possible loosening of fixings, disturbance of glazing seals	—	Lightweight cladding, sheet siding	Noise discomfort to occupants; possible rain penetration past seals by "pumping" action of glazing or spandrel panels. Natural frequency of cladding or panels may influence response
7 Physical changes: a) Loss of volatiles	Contraction, loss of plasticity	Short or long term depending on materials, exposure	Some sealants, some plastics	Contributes to age-hardening of some sealants. May lead to embrittlement and distortion of some plastics
b) Ice or crystalline salt formation	Expansion and possibly disruption in some building materials	Dependent on weather conditions	Porous natural stones, very exposed brickwork	Damage usually confined to spalling and erosion of surfaces

Category 1: Fine cracks up to 1mm; easily treated during normal decoration. Cracks rarely visible in exterior brickwork. Degree of damage: **Very slight.**

Category 2: Approximate crack widths up to 5mm. Cracks easily filled; redecoration probably required; recurrent cracks may be masked by suitable lining; cracks not necessarily visible externally; some external pointing may be necessary; doors and windows may stick slightly. Degree of damage: **Slight.**

Category 3: Crack widths from 5mm to 15mm and the maximum number of cracks less than three. The cracks probably need some opening up and can be patched by a mason; re-pointing of external brickwork required; a small amount of brickwork may need to be replaced; doors and windows sticking and require easing; service pipes may fracture; weather-tightness impaired. Degree of damage: **Moderate.**

Category 4: Variable crack widths from 15mm to 25mm. Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows; window and door frames distorted; floors sloping; walls leaning or bulging; some loss of bearing for beams and joist; severe disruption to piped services. Degree of damage: Severe

Category 5: Crack widths in excess of 25mm (although depending upon number). Involves major repair work and partial or complete re-building; beams lose bearing; severe bulging of walls requiring shoring; windows broken or distorted; danger of instability. Degree of damage: **Very severe.**

However, when assessing brickwork failure due note of the degree of damage should be observed. The location and function of the building may also influence any remedial work. Crack width should not be a sole indicator of failure. Direction, deviation of slope and the number of cracks should also be noted.

Other problems related to brickwork failure may be attributed to inadequate <u>connections, anchors and support systems</u>.

Connections often fail as a result of design/construction errors, e.g. where the structural frame, concrete or steel, is out of tolerance. (Field modifications often exacerbate this problem through the use of excessive shims, horizontal connector plates, or other "ingenious" makeshift solutions. These site based modifications may lead to excessive flexibility in the frame or an inadequate strength.)

<u>Dampness in Rendered External Walls</u>: Typically preceded by defects in the external skin of rendering. Cracks, which sometimes go through the whole wall section, and other weak areas are common especially on the prevailing weather side of the building. The

consequent damage may show itself in contamination by black fungus and peeling of internal wallpapers, and other finishes and plaster.

Points for consideration:

* External rendering does not only fulfil the visual function of a uniform external cladding, but also represents an effective protection against rain which is indispensable in a number of wall construction materials, especially very absorbent or porous materials (e.g. lightweight blocks, light pumice concrete blocks).

* Damage by damp in rendered buildings is mostly caused by defects in the rendering; methods aimed at achieving crack-crack-free rendering also represent significant measures for achieving a cross-section which is protected against heavy rain. Causes of cracks are movements of the wall or the rendering and the inability of the rendering or the adhesive bond between the layers to take up these movements without structural failures.

* Even in rendering without weak areas, precipitation dampness gets into the wall cross-section by capillary action. The extent of capillary conductivity is influenced by the mortar compound, the absorbency of the wall, the subsequent treatment of the mortar during hardening and by water-repellent mortar additives and surface impregnation.

* The permanent water-proof cover is finally determined by the storage capacity of the rendering and the main brickwork or blockwork and by the likelihood of water that has penetrated being expelled again during the drying period. The storage capacity is also dependent on the thickness of rendering. The expulsion of dampness which has penetrated through defective places during construction can only be achieved in water-proof rendering by diffusion; where there are water barrier skins it is completely prevented.

Recommendations for the avoidance of defects:

* In order to achieve a water-proof external wall, conditions which guarantee a plaster surface free from cracks should be aimed at in the production and preparation of the base wall to be rendered and in the choice of material, method of application and subsequent treatment of the rendering.

* Junctions to other structural elements must be carefully sealed (e.g. with permanently flexible sealing compounds). They should not normally be rendered over.

* For walls stressed by rain, water-proof or at least water-retarding renderings are preferable; however, they must permit

an adequate exchange of water vapor between wall section and the outside air. This can be achieved by suitable, water-proof mortar additives or by appropriate external coatings. The setting of the rendering must not be detrimentally affected by this.

Points for consideration:

* Although externally applied thermal insulation layers are basically preferable in residential buildings, especially because of their better protection of the interior and of the structural elements from temperature variations, this arrangement causes problems in rendered structures. The tendency of the rendering layers to expand is particularly great and fluctuates for a limited period when the thermal loading and temperature fluctuations are particularly high due to the thinness of the rendering and the low heat conductivity of the base (localization of heat).

* Furthermore, these tendencies to expansion cannot be continually prevented by a shear connection with the wall; they accumulate due to the adjustable fixing leading where there is partial resistance to high stresses. Finally, dampness can penetrate into the thermal insulation layer through cracks in the rendering which are insignificant in themselves, collect there in cavities, soak through the wall and in examples of swelling insulation materials can cause bad failures in the rendering or reduce the thermal insulation value.

* Thin, mesh-reinforced, plaster-like synthetic resin coatings on polystyrene foam slabs can only absorb these stresses without damage if they are not mechanically stressed; if tension-proof non-degradable mesh inlays are used, which must be well overlapped and strengthened at all corners and openings connections; if the polystyrol foam slabs are fixed over the whole surface of the base especially at the slab edges (clean, dry base, profiled slabs); and if dry polystyrol foam slabs which have been stored for some time are used. To begin with, shrinkages of up to 1/8" (3mm) per 40" (1 metre) in the course of a year can be expected.

Recommendations for the avoidance of defects:

* The surfaces of external walls to be rendered should be of a uniform strong material without defects (open joints) and unevenness.

* Dry clean bases should be wetted in advance; smooth and very absorbent bases should be treated with a rough plaster spray at least 12 hours before the beginning of the rendering work.

* At the function of adjacent structural elements and when the base consists of large areas of differing materials, the rendering should have expansion joints.

* Narrow strips of differing materials in the base (e.g. reinforced concrete lintels) should be bridged with galvanized metal lathing with at least 4" (100mm) lateral overlap.

* External walls made of very absorbent, soft, large block material (e.g. lightweight thermal blocks), external walls with great unevenness as well as external walls with frequent irregular material changes in the base should if possible not be covered with mineral external rendering. If such bases must be rendered, rendered panels reinforced with metal lathing mesh should be used.

* External rendering must be applied at least 3/4" (20mm) thick. The one coat (in lightweight mortar) and two coat (in ordinary mortars) layer of rendering should be applied by hand or with a machine only on a carefully prepared base, so that it bonds in with the base.

* Rendering layers must have a fall in strength in the base from inside to outside. Premixed mortar should be used especially if site working leads one to anticipate a lack of uniform mortar quality.

* Sealing additives, which are advisable especially in the case of walls stressed by rain, should preferably have a coating of rendering at least 1/4" (5mm) thick.

* If possible, rendering should not be done in direct sunlight and strong wind; if necessary the freshly rendered surfaces should be protected by tarpaulins or be kept moist during hardening.

* Rendering should if possible have a moderately rough surface - scratched rendering surfaces are preferable.

* Scaffolding should be erected in front of the wall at a distance of 1'0" (300mm) and be anchored, e.g. by scaffolding pegs, so that no subsequent work is necessary on the rendered wall surface. The work should be divided up in such a way that adjacent surfaces can be completed without interruption to work.

Further Points for consideration:

* External rendering less than 3/4" (20mm) thick frequently form cracks, especially as very thin patches can then occur with only small unevenness in the base.

* With normal rendering mortars a minimum thickness of 3/4" (20mm) makes it necessary to render in two coats.

* If hard outer rendering coats which bind well are applied o a softer base, the shrinkage stresses which occur lead easily to cracking and peeling. The strong thermal loadings of dark surfaces have an equally detrimental effect.

* If the base or the first rendering is proofed, the adhesion of the next layer of rendering will be lower due to the reduced absorbency.

* The water necessary for hardening can be extracted from fresh rendering by water emission to the base and by high temperatures, sunlight and wind.

* In smooth rendered surfaces an external zone rich in bonding agents forms, which has a tendency to shrinkage cracks. Very rough surfaces soil quickly.

* Junctions where work has been interrupted and places on the surface which have been finished later (scaffolding holes) produce not only a difference in color, but also frequently cracks in the rendering.

The best form of construction has a layer of air between the outer slab and the thermal insulation layer; this prevents heat condensation, and thus further heating up of the outer slab, and also preserves the thermal insulation layer from possible saturation from outside.

6. The longitudinal joints within the wall cross-section, which act as a dampness control, should be laid 3/4" (20mm) thick and be completely filled with mortar. External walls which are particularly exposed to rain would, however, be better constructed as cavity walls.

7. Solid brickwork should, if possible, be made of bricks of the same quality, structural characteristics and date. Brick and mortar materials should always be free from foreign bodies and should be frost-resistant. Factory-produced dry mortar eliminates a series of instability factors and is therefore preferable.

8. A soft, plastic mortar should be used to fill all the joints, thus excluding any cavities. Subsequent jointing of the solid surface should be avoided if possible.

9. With solid concrete walls, especially where there is subsequent treatment, care must be taken to ensure adequate covering of the reinforcement, particularly over the cross ties. The covering should not be less than 1" (25mm) thick

and the particles should be 1/4" (5mm) larger than the largest aggregate existing in the concrete.

10. If solid concrete surfaces are to remain free of cracks, movements resulting from shrinkage, creep and temperature stress caused by graduation of the aggregate, concreting curing time, steel reinforcement and positioning of expansion joints should be kept as small as possible.

11. To avoid, as far as possible, subsequent differences in color and changes in structure, the type, color and structure of solid concrete produced later should be consistently laid down (i.e. by use of a test specimen).

12. Impregnations and coatings on pre-impregnated bases must be used as additional protection where solid brickwork or concrete is subjected to heavy rain. However, every wall must also be able to function without impregnation.

13. Mortar and concrete used for impregnation must have adequately fine aggregate and the base to be treated must be clean, free from blistering, absorbent, dry and free of cracks. Cracks must not be wider than 0.15mm and must not subsequently increase due to shrinkage or temperature stress of the components.

14. In order to maintain effectiveness, the coating or impregnation must be renewed at frequent intervals.

Single skin brickwork is especially susceptible to soaking by rainwater if:

* the jointing is inadequately carried out
* inferior bricks were used
* the brickwork was exposed to heavy rain without protection.

Recommendations for the avoidance of defects:

* External walls made of single skin brickwork should only be constructed when investigation into the effects of rain and wind caused by topographical conditions, the local climate and the orientation of the building exclude pressure due to heavy rain. Where there is pressure caused by heavy rain, other types of construction (e.g. cavity brickwork) should be used.
* For normal rain stress the following should apply:
* The wall thickness should not be less than 15" (375mm)

* Brick and mortar material must be matched in their absorbency and capillary capacity

* External and internal brickwork should consist of bricks of equal absorbency, strength and capillary capacity

* All mortar joints - especially the bonded 20mm thick joints within the brickwork - must be free of cavities

* Brickwork and mortar material should permit free vapor diffusion.

* If the appearance and character of solid walls are not to be sacrificed, external walls made of solid brickwork and concrete which are to satisfy the requirements for surface temperatures, surface condensation, comfort and energy saving, should include additional internal insulation measures which are economically viable, or another type of construction should be chosen (cavity brickwork or concrete with core insulation). The thermal insulation value of the whole wall section should not fall below that specified in the local code.

* If thermal insulation layers applied inside are not made of a material with a high vapor resisting value (e.g. hard foam panels) they should be protected by a vapor barrier inside the room.

* Wall constructions with an internal thermal insulation layer, especially those with core insulation, should be checked for their capacity for movement due to thermal liner expansions. If necessary they should be fitted with expansion joints at adequate intervals. Preferably a layer of air should be provided between the outer slab and the thermal insulation layer, which on the one hand prevents localization of heat and thus further heating up of the outer slab, and on the other hand protects the thermal insulation layer from external water penetration.

* Solid brick walls should have a minimum thickness of 11" (275mm). The bonded joint which acts as a vapor control runs within the wall cross-section and should be laid 3/4" (20mm) thick and be filled with mortar. External walls which are under particularly strong rainfall pressure should, however, be of cavity construction.

* The solid brickwork should if possible consist of bricks of the same form and the same quality. Brick and mortar material should in any case be free from foreign substances and be frost-resistant.

* The mortar used should be as soft and flexible as possible in order to avoid cavities completely. Thereby subsequent pointing of the surface can hopefully be avoided.

* With solid concrete wall, especially in cases of subsequent treatment, care must be taken to ensure adequate covering of the reinforcement, particularly over the cross ties. It should, especially where walls are made of in situ concrete, not be less than 1" (25mm) thick and be 1/4" (5mm) larger than the largest size of aggregate.

* If solid concrete surfaces are to remain largely free of cracks, movements resulting from shrinkage, creep and temperature stress due to gradation of granule sizes, concreting time, steel insertion and arrangement of expansion joints at adequate distances should be kept as low as possible. Where there is high humidity and high demands on the concrete, the crack width should not exceed 0.2mm or 0.1mm and in climatic conditions which encourage the risk of corrosion (e.g. in industrial areas) it should not exceed 0.05mm.

* Type, color and structure of concrete produced later should be made compatible (e.g. by use of a sample piece).
* Impregnations and coatings on pre-impregnated bases should be used as additional protection measures for solid brickwork and concrete walls stressed by precipitation.

* Mortar and concrete to be impregnated must have sufficiently fine aggregate particles and the base to be treated must be clean, free of efflorescence, absorbent, dry and free of cracks. Cracks should not be wider than 0.15mm and they must not be subsequently increased by shrinkage or temperature stress of the element.

* In order to maintain effectiveness, the coating or impregnation must be renewed at adequate intervals of time.

Movement and Sealants (Caulking): Movement can be accommodated by expansion and control joints. An expansion joint enables an entire structure to both expand and contract. A control joint provides for movement in an isolated portion of the system; in concrete masonry a control joint should provide a bond break to accommodate both short- and long-term expansion. Control joints should also provide for reversible movement due to changes in thermal and moisture content. To totally avoid cracking, control joints should be spaced approximately 20 to 25 feet for clay masonry, and 8 to 12 feet for concrete masonry. Also, new joints are often cut into existing masonry to accommodate movement.

Sealants often fail under tensile splitting or compression. Many designers specify expansion joints to accommodate wall movement while totally disregarding the ability of the sealant to follow this movement without failing. Failure thus occurs due to either an insufficient number of joints or by providing an inadequate width of joints to accommodate the movement of the sealant. Therefore, the size and spacing of expansion/control joints is critical for sealants to perform properly.

Modern sealants expand or contract a maximum of several hundred percent in the lab before adhesive bond or cohesive internal failure occurs. But in the field, fatigue from movement, ultra-violet exposure from direct sunlight, or age can deteriorate even the best-prepared joint sealant. For example, sealants such as silicones or polyurethanes are incapable of increasing or decreasing by more than at most 30 percent of their original size. In addition, south and west elevations of a building generally show the first symptoms of a problem.

When sealant failure does occur, note whether the type of sealant failure is one of adhesion or cohesion. An adhesion failure indicates a loss of bond between sealant and masonry, perhaps because the masonry was not properly prepared for sealant application. A cohesion failure indicates an internal stressing of the sealant, perhaps because of improper sealant or sealant configuration.

Proper joint configuration is essential for caulking or re-caulking. A rubber band effect is necessary for most sealants to perform properly. Generally, the cross-section of the sealant should have a center depth approximately one-half its width. Proper preparation is also important. All porous surfaces should be primed. The use of bond breakers in the form of rods or tapes is also essential to the success of the joint. (Typical closed-cell sub-caulking rod stock should be under about 25 percent compression and unscarred after installation.) Use bond breaker (polyethylene tape) for alternate situations to avoid three-sided adhesion. For retrofit work, all old caulking must generally be removed.

<u>Design Omissions</u>: Clarity in design intent will contribute greatly to reducing failures. Specifications should be specific. The following are examples of common specifications omissions:

* Allow maximum spacing of shelf angle bolts from the corner. (nine inches is recommended.)

* Make sure shelf angles are continuous around corners.

* Allow minimum embedment of standard masonry tie in the brick. (A minimum of 2.1/4 inch is recommended.)

* Allow minimum torque required for shelf angle bolts. (A minimum 50 foot-pound is recommended.)

* Allow maximum total thickness of metal shims permitted. (A maximum of 3/8 of an inch is recommended.)

* Exclude all bi-metal contact such as between brass/bronze and mild steel or between stainless and mild steel.

* Allow maximum coefficient of saturation of brick. (Depends on exposure.)

* Exclude stacked stone units where panel thickness is less than 2 inches.

* Allow maximum permissible brick overhang on steel shelf angles. (One-and-a-quarter inch is recommended.)

* Keep back of masonry free of contact with the structure.

* Keep setting pads (used to level stone panels) away from the edge of panel.

* Anchor block backup walls at the top to the structural frame.

* Avoid use of paper or wood sheet within mortar joints.

* Avoid use of "soaps" (brick cut into 2-inch strips) in brickwork.

* Avoid use of joints in steel shelf angles directly over windows. (An excellent "invitation" for water penetration.)

* Set membrane flashing in mastic, attached firmly to backup beams or walls.

* Extend membrane flashing a minimum height above shelf angle. (A minimum of 12 inches is recommended.)

* Lap membrane flashing a minimum of 6 inches at splices and have closures at discontinuous ends.

RESEARCH NEEDS FOR MASONRY

As previously noted, many problems related to masonry construction are basic in nature. The cause and affect of design and construction "errors" are well documented. Innovations such as the GFRC drywall technique are by now common in some sectors, although the majority of work relates to traditional methods of construction. The brick and masonry industry recognizes that additional research work needs to be applied, especially in the area of new construction methods and analytical design. For example, at a recent workshop (10) on masonry research a number of industry experts reviewed the need for advanced research in this field of interest and highlighted a number of critical issues that needed further work. The work was prioritized into nine categories, i.e. (i) new design, analytical and modelling methods, (ii) new assembly systems, units, and joints, (iii) technology transfer, (iv) environmental characteristics, (v) construction technology and workmanship, (vi) instrumentation, monitoring or Tests, (vii) new raw materials and other new material items, (viii) regulatory items - codes, standards, and other restraints, and (ix) production, manufacturing, scheduling and maintenance, (appendix nine).

LIGHTWEIGHT STEEL and BRICK VENEER

Lightweight steel-frame bearing-wall construction is being used more often in low-rise commercial and residential buildings. The long-term performance of lightweight steel framing in structures over three stories is a concern. To date, its use in medium- and high-rise buildings has been mainly for exterior partitions or as non-bearing backup for exterior skins.

Principal Applications and Advantages: Speed of construction, non-combustibility and relative light weight are key advantages of this system. The space between studs eases insulation and accommodates piping and electrical distribution. Because the framing can be completed independent of masonry veneer, the interior is out of the weather quickly and can be finished while the exterior brick veneer is laid. In non-residential construction, where fewer bracing walls, longer vertical spans and horizontal runs are likely, added cold-formed bridging or bracing of the frame increases lateral stability.

Pre-punched holes in the studs provide easy routing of plumbing and electrical lines. Most codes require the use of electrical conduit or that the pre-punched stud opening be sheathed, to avoid stripping the insulation as wires are drawn through. Electrolytic action between framing members and nonferrous plumbing pipes must also be considered and pipes on exterior walls must be adequately insulated.

Key Integration Issues: Deflection in lightweight steel frame construction can be several times that of the exterior masonry veneer; these differentials must be accommodated in anchoring details or overcome by adding structural rigidity. Anchoring the veneer to the steel frame should permit free and independent movement of the two materials. Where the veneer depends on the steel frame for lateral stability, anchors should be flexible and not resist shear. Wire ties that allow independent movement are recommended.

Sheathing both sides of the frame provides some lateral stability. Steel studs used for masonry backup should also be cross-braced with steel straps. Horizontal and diagonal bracing increases the frame's rigidity. Welded connections are stronger than self-tapping screws. The method of attachment can have substantial cost implications.

TILT-UP WALL

Load-bearing tilt-up wall panels provide a UNIFIED vertical envelope, structure and interior. The panels are precast on-site, generally using the floor slab or grade as the casting surface before being tilted or lifted into position.

The wall panels, usually 6 inches in nominal thickness, may extend from one to several stories in height, and must be designed to withstand the bending loads involved in tilting and lifting, as well as loads that will be encountered once in place. They may be plain, reinforced, or prestressed and are often provided with temporary timber or steel "strongbacks" for tilting, particularly where there are large window openings.

The panels must be braced during construction until all wall and roof structural members are in place. Columns are usually cast in place following installation of the panels. In load-bearing tilt-up wall systems the roof and floor members are bolted or welded to plates and angles cast into a continuous ledger beam.

Principal Applications and Advantages: Tilt-up walls have been used routinely in a variety of building types and heights, especially for single-story buildings with large, uncomplicated exteriors. The system is also increasingly used for multistory, low-rise projects. It is suggested that significant savings in time and formwork costs can be achieved a. Hence long lead times required for precast or structural steel components may be averted.

The building shell can be erected quickly, permitting interior work to proceed along with final joining and sealing of the envelope panels. Because most of the forming and erection work is done within the floor slab area, tilt-up systems work well in confined construction sites.

Key Integration Issues: Conservation of time and forming material is realized when there is uniformity in panel design and when the floor surface can be used for forming. Careful planning of the forming, storage and lifting sequence is essential, and early consultation with manufacturers and contractors is advisable. Because the floor slab on which the panel is cast must be smooth, utility raceways, pipes and conduits that will penetrate the slabs must be stubbed below the finish slab level, covered during wall panel casting and then uncovered for final connections.

Regular inspection of casting and lifting operations is essential. Joints between panels should be designed to be concealed. (This is easily accomplished where cast-in-place columns are designed to lap the panel edges, or where the panels insert at their edges into a precast column channel.) Connections between panels should not be rigid, so caulks and sealants are important.

Mechanical and interior systems are generally combined at a connected level to the structure and envelope. The location and installation of angles, channels, weld plates, conduits, connectors and other hardware should be carefully planned and detailed, with regular and careful inspections before placing the concrete. Lifting forces and special complications due to openings require exacting structural analysis and special erection hardware.

Foundation and slab detailing are the key to preventing water infiltration at the panel bases. It is good practice to design the system so that the slab level is slightly above the bottom edge of the vertical tilt-up panel.

CLADDING TO FRAME CONSTRUCTION

Metal panels are generally accepted for use in curtain walls, infill, spandrels and fascias. The pre-fabricated, insulated units discussed here differ from metal "sandwich" panels in that the metal encapsulates the insulation and does not require internal fasteners or subgirts,(11).

The metal panel concept represents a unification of envelope and interior.

Metal: Metal panels can be made of aluminum, stainless steel, or galvanized or other coated steel. The choice is both economic and aesthetic. Stainless steel seems to exhibit the most problems with distortion, or "oil-canning". Metal thickness, alloy and, in the case of aluminum, temper, will all affect the appearance and durability of the panel.

Exterior and Interior Faces: The faces need not be the same finish or thickness of metal. It is best to consult the manufacturers' literature for details on available sizes, color and assemblies. Surfaces may be flat, textured or extruded, have an impressed relief pattern or be cast to match a custom design. The degree of exposure desired for the interior face will determine whether it receives an applied finish or has a mill finish meant to be concealed. Some manufacturers will assemble a panel with an interior face of plywood or other rigid material.

Connections: A range of proprietary connection methods is usually available with a given manufacturer's panel. The connection detail will depend on loading conditions.

Finishes: Painted, baked enamel and porcelain enamel finishes are available for steel and steel alloys, while aluminum panels are either painted or anodized. Stainless steel does not usually have an applied finish. Both aluminum and steel may be ordered with factory prime coats for field painting, but this is the lest reliable finishing method. Painted and anodized finishes are available in durable and attractive colors. Anodized finishes are not recommended for applications where they would be exposed to salt water or corrosive pollutants. The patented factory-applied paint finishes have proven very durable, and many come with a five-year warranty. The designer should determine whether the finish coat is applied by the metal manufacturer or the panel fabricator.

Finishes for cladding

1. Silicone-modified polyester (SMP);

2. Fluorocarbon (PVF2);

3. Stainless steel;

4. Anodized aluminum.

Stainless steel is very expensive. Anodized aluminum is costly and it is very difficult to achieve color match, as any variation in alloy or time in the anodizing bath will cause color variation. Generally speaking, the pre-painted steel sheet finishes will offer better color ranges and are cheaper. However, their durability beyond 15 years cannot be guaranteed. All paint finishes are affected to some degree by ultraviolet light and will fade with time. PVF2 has the best color stability but its coat (25 microns) needs protection during assembly of panels on site. Touch-up paints are available for minor scratches.

Testing and quality control

Architects should request evidence from manufacturers that their products fully satisfy the performance requirements in the form of test date. With integrated systems, the manufacturers ar now taking on responsibility for the complete envelope, This leads to a requirement for more adequate testing of not only the parts but also the combination of the individual components.

Manufacturers should only offer fully tested solutions, but this, unfortunately, is not always the case. Many systems on offer are under-resolved, almost like second-generation prototypes rather than completely designed and developed products.

In common with all manufactured products, quality control is vital to ensure satisfactory completion of the facades. Architects should not just seek compliance with standards, but must also be prepared to ask manufacturers for evidence of their quality-control procedures and to monitor them at intervals as the job progresses.

A further difficulty is that cladding technology has out-paced the production of standards, and architects can no longer solely rely on specifications covering particular systems. Areas falling outside the scope of standards should be adequately covered by the project-performance specification.

Thus the development of panel systems together with many components used in modern construction demands an increased dialogue between architects, manufacturers and contractors on such issues as fixing and jointing techniques, types of finishes and quality control on sites. Poor control of detailing will spoil the effect of the best panel production. It is essential that architects join with manufacturers to discuss the details for any particular project, and, where possible, they should seek tenders from those manufacturers who offer a complete design fabrication and installation service to ensure a quality product.

Cladding and its frame

Non-load bearing cladding, often in panel form, is most commonly used in conjunction with a structural framework of either steel or concrete. However, it is only in the last 15 to 20 years that buildings have been constructed, taking full advantage of frame construction, e.g within the envelope of the building panels become fully interchangeable: doors (even loading-bay doors) can be relocated, windows combined with insulated panels or louvres exchanged with windows. The possibilities of combination are considerable and the technology to achieve this is now readily available. Strict modular coordination is essential to make it possible. Dimensional control linked with controlled sizing of accurately made machine-produced panels allow panels or louvres to be replaced over the life of the building.

<u>Composite metal panel</u>: Many materials can be used for cladding, e.g. precast concrete profiled metal, Glass Reinforced Plastic (GRP), Glass Fiber Reinforced Cement (GFRC) and curtain walling. However, it is the use of composite panels and, in particular, composite metal panels, which are now in increasing use for all types of buildings. This increase is partly due to the introduction of improved insulation, thus leading to the development of composite insulated panels and overcladding systems. It is also a factor of the desire to reduce the amount of support framework by increasing the spanning performance of composite panels.

In this way spans of 10'-17' (3-5m) can be achieved compared to 5'-8' (1.5m-2.5m) with single-sheet profiled material. Use of sandwich panels with their self-finished interior and exterior skins can also show definite advantages in speed of assembly provided that the method of fixing allows efficient placing of the units which, being lightweight, can normally be handled by two men.

Composite construction principles are applied to cladding panels whereby two sheets of metal are held apart by core material to which both sheets are bonded. It is the spacing of the two metal sheets which is predominantly responsible for the rigidity of the final composite. Basically, the wider the spacing, the greater the spanning capabilities of the finished product.

The benefits of composite constructions are:

* Light weight.

* Long span (longer than profiled single sheet metal, i.e. for the identical load criteria: a typical profiled sheet spans 5' (1.5m) - a composite spans 13' (4m).

* Provision of insulation - if core selected, it has an insulation performance (e.g. polystyrene or polyurethane foam).

* A combination of the advantages of different materials.

* Accurate manufacture in factory conditions which leads to precise appearance/image.

* Fast erection time - direct-result, large-size accuracy of manufacture.

* It is self-finished inside and out - it only requires a frame and it is a complete building envelope;

* Flexibility - its lightness facilitates relocation and even replacement.

The major turning point for lightweight composite cladding panels occurred in the 1970s. A growing awareness, which led to a realization of the need to conserve energy led to improvements and design innovations. Thus the thermal performance of the building envelope became much more important, and this, in turn, led to a greater concern for insulation and insulated panels.

An early example of these changes was Foster Associates design in 1977 of the Sainsbury Centre in the U.K. The design incorporated new technology that incorporated interchangeable components. The project was also was one of the first to use Superplastic Aluminum for insulated composite cladding panels. More importantly, it was one of the first non-commercial , non-industrial buildings (it is an art gallery) to use an interchangeable panel system. It is a building which has gained an international reputation and has stimulated the development of component-based architecture throughout the world. Identical 6' x 4' (1.8m x 1.2m) panels were used for both walls and roof, and the joint detail depends upon the neoprene gasket being mounted back against an aluminum carrier system.

Sadly, perhaps because this was such an early example of the application of these principles, the original panels have had to be replaced by flat white ones manufactured in the USA by Cupples Product Divison of H.H. Robertson, which has transformed the aesthetic appearance of the building. (One of the disadvantages of being ahead of the state of the art in building is that all the characteristics of the construction may not be known at the time of the design. In this case, it is said that moisture inherent within the phenolic foam has built up, causing corrosion on the panels leading to their replacement.)

<u>Types of assembly</u>

Essentially, there are three types of panel assemblies:

1. Panel-to-subframe assembly, whereby the panels are jointed by subframe curtain walling carrier systems, normally in aluminum, which is, in turn, fixed back to the main framing;
2. Panel-to-panel assembly, whereby panels are jointed to each other and fixed directly back to the main structure or secondary framing;

3. Rainscreen panels (see later discussion), whereby an outer panel provides a weather shield to the insulated inner one. As the name 'screen' suggests, these panels are only a first-stage barrier.

Panel-to-subframe assemblies

Here, steel- or aluminum-faced panels, with either laminated or foamed insulation cores, are mounted onto a curtain walling type subframe using structural gaskets. The perceived advantage of the panel-to-subframe assembly is that it offers the opportunity of interchangeable window/wall panels with a similar joint on all four sides of the panel.

There are many manufacturers offering proprietary systems of this nature. With panel-to-subframe assemblies in particular, the cross-over junction of horizontal and vertical joints is critical for weather-tightness. The method of connecting the mullions and transoms and the tolerances of cutting aluminum sections and their assembly is critical to achieve a water- and airtight joint.

Panel-to-panel assemblies

Here, the panels are linked together, often incorporating a secret fixing within the joint. Various types of joints are possible between panels, including:

* Tongue and groove details.

* Overlap details.

* Compressed seals using continuous channels.

* Face-applied gasket systems.

* Top-hat sections.

Although most proprietary panel-to-panel systems have windows mounted within the panel it is also possible to provide a window-to-panel solution by means of a third member or jointing piece. The horizontal and vertical joints will be different, thus offering less interchangeability. Panel-to-panel assemblies, particularly those using tongue and groove joints, normally rely on sequential stacking. If panels have to be replaced due to damage they are best arranged in bays.

Panel-to-panel systems are now being developed which allow windows and doors to be assembled directly to the panel.

With careful detailing it is possible to instal panel-to-panel assemblies vertically, horizontally or a combination of both.

RAINSCREEN CLADDING

A great deal of research, both in North America and Europe, has been devolped over the years into "rainscreen cladding", (Appendix 10).

> *"Consideration of the functions required of an external wall has led to the concept of a wall with an inner structural leaf, insulated on its outer face, and a cladding assembly to protect the inner leaf from the effects of heavy wetting and solar radiation. Locating the insulating layer on the outer face of the inner leaf reduces thermal expansion and contraction of the building structure, avoids localized cold bridging around structural members, and reduces the risk of condensation on or within the inner structural leaf. The provision of an external rainscreen with an airspace which can be drained, back-ventilated and, if required, pressure equalized also means that the main portion of the wall is not subjected to deleterious effects of intermittent rain, and the risk of the through-wall penetration is minimized. Finally, the rainscreen serves as a cosmetic element." (12)*

This type of system depends upon an outer layer of flat metal sheet approximately 4.6mm (3/8") thick mounted in front of laminated panels with a ventilated cavity between the two parts of the construction. These sheets, usually butt jointed, offer a first protection against driving rain (rainscreen). The panels behind provide the thermal and acoustic performance and can be mounted into a carrier system or fixed to secondary framing as in previous examples.

Small butt joints between panels are possible using this method. Provided that an adequate external-grade lining can be attached to the outside face of the laminated panel then the size of the panel is only limited to the maximum size of the plate panel and its ability to span between supports. The gauge of the plate panel must be such as to avoid rippling and distortion of the sheet.

Rainscreen panel systems are increasingly being used as a method of upgrading existing facades, particularly for high-rise buildings erected in the 1960s and now in need of repair or improved external insulation.

<u>Rainscreen or protected walls</u>: a traditional example of rainscreen technology is the tile-hung wall. With the rainscreen, or two-stage technique, the rain and wind barriers are separated by an airspace. The outer leaf or 'rainscreen' provides the major barrier to rain penetration and the inner leaf of the wall, which forms the air-barrier, is kept relatively dry. If the air barrier and the joint seals on the inner surface of the cavity are not allowed to become wet, they cannot leak to the interior.

*There are two distinct rainscreen techniques. First there is the drained and back-ventilated rainscreen which involves draining off most of the rainwater at the outermost surface of the wall and providing for cavity drainage and evaporation of the remainder. Second there is the pressure-equalized rainscreen. Here the aim is to eliminate penetration through the rainscreen not by tightly sealing joints, but by leaving some or all of the joints open to the passage of air **but not water**. The main difference between the two techniques is the degree of importance attached to the ability of the joints within the rainscreen to prevent penetration without the use of gaskets or sealants.*

Common to both, however, is the provision of an air space immediately behind the outer-leaf which can be drained and ventilated.

Drained and back ventilated rainscreen

The drained and back-ventilated method of rainscreen design was pioneered in Scandinavia, and is now commonly used in parts of Europe. Flat, impervious materials such as fiber cement sheet, pre-finished aluminum, pre-finished galvanized steel and large ceramic tiles have been used to construct lightweight cladding for both new and remedial works. In its simplest form, the technique consists of a series of thin impervious flat sheets, pressed metal panels or planks fixed to vertical support rails. The joints are designed to provide protection against kinetic energy of wind driven rain. This is achieved by incorporating baffles or by stringently controlling the width of the narrow open joints. These joints obstruct the passage of wind-driven droplets of rainwater, but they do not prevent leakage due to gravity and wind-induced air pressure differentials. Thus relatively large quantities of rainwater penetrate the joints and run down the reverse, hidden face of the cladding assembly. Successful design depends upon preventing this water from reaching the inner leaf in sufficient quantities to cause heavy wetting. Water within the cavity is drained, and positive back-ventilation is used to promote the rapid evaporation of any rainwater deposited on the inner leaf. The same process is used to evacuate the water vapor which permeates through the inner leaf and its insulating layer.

Typical guidelines for drained and back-ventilated rainscreen include:

1. Incorporate baffles in all vertical joints between thin sheet cladding panels. Overlap or interlock pressed metal panels and vertical planks to form vertical joints with integral baffles.

2. Incorporate baffles in all horizontal joints between thin sheet cladding panels. (Research indicates that where a horizontal gap is <= 1/4" (5mm), very little water will cross an airspace which is at least 1" (25mm) wide.) Overlap or interlock pressed metal panels and horizontal planks to form horizontal joints with integral baffles. Fit baffles to horizontal joints between vertical pressed metal planks.

3. Use vertical support rails wherever possible, as this encourages the rainwater to drain freely down behind the cladding assembly. Horizontal support rails should not be specified unless steps are taken to ensure that they do not impede the flow of rainwater, as this may cause splashing across the air space. When possible, slope all structural connections down and outward towards the outside face of the cladding.

4. Ensure that the airspace cavity is >= 1" (25mm); allowances for site erection tolerances and the use of non-rigid insulation should be noted.

5. Fix and seal all window and door elements to the inner leaf.

6. Introduce cavity closures at the top and corners of the building so that the zones of positive and negative wind pressure are separated. Do not install intermediate vertical or horizontal cavity closures unless they are required for smoke and fire control. Slope any horizontal closures down and out to induce positive drainage.

7. To promote the raid evaporation of residual water and/or condensation within the cavity or outer layer of thermal insulation make the joints or junctions forming the ventilation at least 3/8" (10mm) wide and provide a minimum free area of 0.01m (2) per linear meter (40") of cladding. (Note, for ventilation openings >= 3/4" (20mm) a vermin mesh should be provided.)

Pressure-equalized rainscreens

The technique of pressure equalization is now well accepted and widely employed in a variety of window, curtain wall and wall constructions, where the presence of an air-space is exploited as a means of controlling the effects of wind action. It has become particularly associated with the design of multi-leaf walls with lightweight rainscreens.

In the pressure-equalized technique, the effects of kinetic energy, surface tension, gravity and pressure-assisted capillarity are controlled by incorporating baffles, labyrinths, drips and upstands in the joints in the cladding assembly. Rain penetration caused by wind-induced air-pressure differentials is attenuated by pressure equalization, which is achieved by incorporating protected openings of adequate size within the rainscreen. The nature of wind-flow patterns around buildings makes the ideal condition of full pressure equalization impossible to achieve with certainty. Therefore an intelligent compromise needs to be adopted, which entails minimizing the wind-induced air-pressure differentials across the joints in the rainscreen, while controlling any leakage process which may be at work.

The main point to note about the pressure-equalized rainscreen approach is that, without relying on the use of sealants (caulking) or gaskets, every effort is made to eliminate leakage through the joints in the cladding assembly. There may, however, be some minor leakage into the cavity and a precautionary drainage mechanism is therefore necessary. Positive back ventilation is also used to promote the rapid evaporation of residual rainwater and to evacuate the water vapor which permeates through the outer leaf.

Typical guidelines for pressure-equalized rainscreens include:

1. *Joints within the cladding assembly must be designed to give a high degree of resistance to rain penetration.*

2. *An effective and continuous barrier against air infiltration on the internal side of the cavity must be provided.*

3. *The airspace within the cavity must be divided into a series of compartments so that the air pressure can be equalized.*

4. *Provide protected openings within the cladding assembly to minimize wind-induced air-pressure differentials acting across the rainscreen. (The protected openings ensure that high degree of pressure equalization is achieved. They are best located in the soffits of sheltered, baffled horizontal joints.) Horizontal joints should be at least 3/8" (10mm) wide; a joint design of 3/4" (20mm) is recommended.*

5. *The permeability of the rainscreen cladding must be many times greater than that of the inner leaf. (Researchers indicate that a permeability ratio ranging from of 10:1 to 25:1 would be adequate.)*

6. *Introduce cavity closures at all corners and at the top of the building to minimize the lateral and vertical movement of air between the zones of positive and negative pressure.*

7. *Subdivide the cavity by introducing intermediate vertical closures spaced 4' (1.2m) to 5' (1.5m) on center at the corners and 17' (5m) in the mid-regions. Horizontal closures would be introduced at each double story height or 34' (10m). (Cavity closures need not provide a complete air seal, but ensure that they offer sufficient resistance to air flow to allow pressure differences between compartments to develop. They must also possess sufficient strength and rigidity to withstand the air-pressure differentials which across them.)*

8. If a flush appearance is not required, fix and seal the window and door elements to the inner leaf and use the cladding assembly to protect the perimeter seals. If a flush appearance is required ensure that the cavity closer around the window and door elements are (i) relatively airtight; (ii) protected against the effects of heavy wetting; (iii) capable of withstanding the air-pressure differentials which act across them.

Drained and back ventilated -V- Pressure equalized rainscreens

As a general rule, a cladding assembly based on the drained and back-ventilated approach will cost less than one that utilizes the same materials but employs the technique of pressure equalization. With the drained and back-ventilated approach, the flat panels with simple square edges can be fixed directly to vertical support rails. The joints between the panels are easily baffled using components which need to be designed to provide protection only against the kinetic energy of wind driven rain. In contrast, all the joints in a pressure-equalized rainscreen must be designed to counteract all the processes tending to force or carry water to them. Large protected openings must also be incorporated within the rainscreen, and this invariably involves overlapping and interlocking the cladding panels to form labyrinth joints which permit the passage of air but not water. In addition, intermediate horizontal and vertical cavity closures must be incorporated to inhibit the flow of air within the cavity from areas of higher wind pressure to areas of lower wind pressure. Nevertheless, if a flush appearance is required, a pressure-equalized rainscreen should be adopted.

The design of the inner leaf and its resistance to rain penetration and the effects of localized wetting must be taken into account when assessing the performance of the two approaches to rainscreen design. Although it is more costly, the pressure-equalized approach has the advantage that it generally provides a higher degree of protection to the inner leaf. (With the drained and back-ventilated approach relatively large quantities of rainwater may run down the reverse side of the outer leaf. Inevitably some of this water will splash on to the inner leaf. If the inner leaf is absorbent, however, and the presence of water does not have a deleterious effect on the material, this splashing of water may not be significant, particularly where a water-repellent insulation has been fixed to the outer surface of the inner leaf.

Common rainscreen materials and surface finishes:

* *Fiber cement sheet - natural or decorated*
* *Fiber reinforced stone composite sheet - textured or aggregate faced*
* *Natural stone - natural*
* *Ceramic panels - glazed*
* *Aluminum plate - anodized or pre-coated*
* *Aluminum sheet - anodized or pre-coated*
* *Steel sheet - galvanized or pre-coated or vitreous enamel*
* *Stainless steel sheet*

Factors relevant to the selection of rainscreen materials and surface finishes

* *Jointing: The working characteristics of the cladding material may influence the method of jointing.*

* *Color: Rain streaking and dirt accumulation are likely to be more noticeable on light colored surfaces, particularly where horizontal profiling is used. The darker the color the*

higher the surface temperature attained by the cladding assembly. Use light colors wherever possible to reduce thermal expansion and contraction. Check for possible color fading.

* *Surface Texture: Face fixings, surface irregularities and panel bowing are less noticeable when textured surfaces are used. These, however, are difficult to clean if non-uniform weathering occurs. The removal of graffiti may also be a problem with textured surfaces. Smooth surfaces are easier to clean, but rain streaking, face fixings and surface irregularities are likely to be more noticeable.*

* *Weight: The self-weight of the cladding material will determine the magnitude of the dead loads which act on the support framework and the building structure.*

* *Strength and rigidity: Thin sheet materials may require surface profiling to give rigidity to the cladding panels. The strength and rigidity of the cladding panel itself will influence the spacing of the support framework.*
Impact resistance: A cladding is more susceptible to impact damage at ground-floor level in public areas, and it may therefore be necessary to use stiffer, more robust materials on those levels to which the public has access. The possibility of damage caused by cleaning cradles (gondolas) must also be taken into account.

* *Fire: When selecting materials and surface conditions note must be taken of such matters as combustibility, flammability and surface spread of flame.*

* *Durability: The durability of a cladding material and its surface depends on a number of factors, including the deleterious effects of sunlight, surface temperature extremes, ozone, frost and the local environmental conditions to which the cladding will be subjected. With regard to the last, special consideration must be given to the selection of materials and surface finishes for use in marine and industrial atmospheres.*

* *Maintenance: The life expectancy , life to first maintenance, and the frequency and method of cleaning must all be taken into account when selecting materials and surface finishes. Consideration of the problem of replacement in the event of a fire or impact damage, and the ease of making minor in-place repairs.*

<u>Support framework</u>

The support framework must be durable and highly resistant to corrosion. Typically, extruded aluminum or stainless steel support rails are used when the drained and back-ventilated approach is adopted. Galvanized rolled steel members may be used to support pressure-equalized rainscreens which have been designed to minimize rainwater penetration into the cavity. However, the corrosion-resistant finish may be damaged or rendered partially ineffective due to cutting and drilling on site. All fixing components should possess a high degree of resistance to corrosion. In general, all fittings such as anchors, coupling bolts, heavy duty washers, locking nuts and self-tapping screws should be of stainless steel. Thin nylon or dense neoprene isolation packs should be used to separate dissimilar metals or metallic finishes. Likewise when contact with cementations surfaces may occur, e.g. concrete and brickwork.

The cladding assembly must be capable of resisting and transmitting to its points of support all life and dead loads to which it will be subjected. These loads will induce deflection and create stresses. It is normal practice to limit the maximum permissible deflection of story-height framing members to span/200. Permissible deflections for the cladding panels themselves range from span/90 to span/500, depending upon the performance characteristics of the materials used.

Adequate provision for thermal expansion and contraction should be provided. The surface temperature extremes will be determined by such factors as location, orientation, color, surface texture; the thermal characteristics of the inner leaf; the efficiency of the back-ventilation process.

In addition, adequate allowances for deformations and movements in the building structure due to shrinkage and creep, elastic deformation, temperature changes and differential settlement. As a guide, instantaneous deformation is typically of the order of 1/3000; shrinkage 1/2000; and creep 1/2500.

Thermal insulation

If thermal insulation is required it should be located on the outer face of the inner leaf and not on the reverse side of the cladding panel. The insulating layer should be attached using non-ferrous fasteners designed specifically for this purpose. The degree of rigidity of the insulation and the method of attachment must be selected to prevent bulging into the cavity and migration downwards. If necessary, an aluminum or stainless steel mesh should be used to support the insulation. The insulation material should be non-combustible, vapor permeable, rot-proof, vermin resistant and water-repellant

Design Practice: Remedial Overcladding

One of the most significant applications of lightweight rainscreens is as a remedial overcladding to existing building, particularly those suffering from some combination of the following problems:

1. *Rain penetration through wall joints.*
2. *Rain penetration at windows.*
3. *Inadequate thermal insulation.*
4. *Localized cold bridging, particularly at floor slab edges.*
5. *Condensation.*
6. *Deterioration of mortar joints in masonry construction.*
7. *Delamination of external finishes such as stucco, mosaics and tiles.*
8. *Concrete spalling.*
9. *Corrosion of reinforcement.*
10. *Sulfate attack on brickwork.*

Overcladding an existing wall structure has a number of advantages:

A. The incorporation of addition thermal insulation for energy conservation and condensation control is relative straightforward. It can be applied to the outside face of the existing wall, where it will overcome the problem of localized cold bridging. In addition, the use of a vapor-permeable insulation together with a cladding assembly which permits cavity back-ventilation means that the building can "breathe".

B. If designed and installed correctly, the new cladding protects the existing wall from the deleterious effects of solar radiation and intermittent rain soaking.

C. Where delamination and spalling occurs, essential repair work to the existing wall may be minimized; additional restraining fixtures may be concealed behind the cladding assembly.

D. The appearance of the building may be altered.

<u>Recommendations for future research</u>: There are a number of areas where detailed future research is suggested in the CIRIA report with regard to promoting a better understanding of the design, performance and testing of rainscreen cladding assemblies:

1. *<u>Performance testing to validate design:</u>*

   Test methods currently used for design validation purposes have a number of shortcomings, e.g. rainscreens are typically tested under simulated environmental conditions which are far less demanding than those which occur in practice. Test methods need to be developed that enable rainscreens to be tested for resistance to air infiltration, water penetration and structural wind loading (positive and negative).

2. *<u>Re-appraisal of current jointing techniques</u>:*

   Past research has predominantly been directed towards the performance of two-stage rainscreen joints such as those used between precast concrete panels. This work should be extended to include those jointing techniques more commonly being used by cladding manufacturers.

3. *<u>The process of cavity back ventilation:</u>*

   Detailed research is required to establish how the efficiency of the back ventilation process is affected by variations in the design of a rainscreen cladding assembly and the inner leaf which it protects.

4. *<u>The process of pressure equalization</u>:*

   The establishment of basic rules for design, particularly with regard to the structural design of rainscreens and the way in which wind pressure act upon them.

5. *<u>Smoke and fire control</u>:*

   No detailed research is available on the behavior of lightweight rainscreens in real or near-simulated fire conditions. What little work has been carried out to date merely serves to confirm that combustible insulation should not be applied to the outer face of the inner leaf, where it will contribute to the spread of flames and may cause structural failure of the cladding assembly. This work needs to be extended with a view to establishing clear guidelines on the type of thermal insulation to be used and the positioning of fire/smoke stops.

It is further recommended that the American Society for Testing Materials "Building Life-Cycle Cost" (BLCC) computer program, (15) or similar, be used to compare alternative wall systems in terms of their economic performance. The BLCC program is comprehensive, allowing the user to assign and define the building system's characteristics. For example, when a for-profit project status is specified, depreciation-related data is requested while the specification for tax-exempt status for a project causes these data requests (and other income-tax-related data) to be bypassed.

Finally, a review of current research programs amongst federally funded groups, private organizations and universities needs to be undertaken in the field of material science and systems. For example, the NISTIR-89 (16) report outlines nine research projects connected with wall systems technology, (Appendix 12).

SUMMARY

During the compilation of the report it soon became evident that many building failures that are associated with wall system technology relate to traditional forms of construction. It also became evident that solutions also exist to remedy these problems. Solutions that should either be "built-in" to new work through the adoption of good practice, e.g. establishing appropriate design and construction specifications; providing adequate supervision during construction; establishing a suitable maintenance, repair and replacement program. In addition, with regard to "new" solutions, their development and acceptance period may be extremely lengthy. For example, work on glass fiber reinforced cement products (GFRC) spans a fifty year period of research and development. During the last ten to fifteen years GFRC has been accepted as a suitable alternative material for many building components, including cladding panels. However, its durability is still under assessment, particularly where it is used to form part of a composite material. Similarly with EIS systems.

This is not to imply that only well tried and tested materials and systems should be adopted, for the adoption of "new" technologies may lead to substantial cost savings. However, a degree of caution is always necessary, especially when direct "in-house" experience is not available. Indeed, one might argue that much valuable information must already exist within the U.S. Army on the performance characteristics of many walling systems. Information that should prove to be of great value in the assessment of existing buildings and in the compilation of maintenance procedures for existing buildings.

Therefore, as a first step it is recommended that the U.S. Army undertakes a retrospective study of existing building stock in an attempt to catalog and identify all failure patterns related to wall systems. Information should be available from maintenance records. This information may already exist in the form of a cost breakdown for budgetary purposes. In addition, defect types and severity levels need to be established. (This work may be similar to the "crack-width" inspection levels set by the BRE and described under the masonry failure section of this report.) In addition, reference should also be made published maintenace procedures, (Appendix 11), and to the pioneering work undertaken by the Center for Architectural Conservation (CAC) at Georgia Tech,(13). This work enables a user to define the level of failure for a building component, in this case a window, and to assess the necessary remedial work. Utilizing a computer database of known building failures, the user is able to identify a potential problem and to solicit advice on the necessary treatment.

Published data on building failures tend to be either too general or too specific, as evidenced by the literature survey undertaken for the report. From a list of over thirty journal articles identified during a bibliographic survey, few articles were found to be specific enough to be of value. Most discussed issue of current concern at a global level. Therefore, as an extension of the data gathering exercise, it may be necessary to undertake field studies on "typical" Army bases to establish levels of defects and severity. Again, the work of the CAC may be of value, particularly with regard to their experience with field laboratory facilities.

As a second recommendation, a life-cycle cost-benefit analysis of existing wall systems currently adopted by the U.S. Army should be undertaken, e.g. review first-costs by reference to published cost estimating databases and by direct contact with industry; maintenance costs and repair costs should be established from internal records, where available; and replacement costs may be identified in terms of calculated life-cycles, again from internal records. By utilizing "in-house" data distortions caused by inaccurate data should be overcome. For example, buildings are typically built of a quality befitting their anticipated purpose and expectation for length of service. Hence, in-house data should overcome any problems with bias. In addition, the problem of the non-disclosure of proprietary research results would be overcome where self-generated data is utilized. During the study, information was obtained from the Masonry Research Institute,(14) to the effect that a detailed life-cycle cost benefit analysis had been undertaken on external wall systems. After lengthy discussion with the authors of the report, the Brick Institute of America and the Masonry Institute a copy of the report was denied. No reasons were forthcoming.

LIST OF APPENDICES

Appendix 1: Allen, E. and Iano, J., "The Architect's studio Companion: Technical guidelines for Preliminary Design", John Wiley and Sons, 1990.

Appendix 2: Mann, P.A., "Illustrated Residential and Commercial Construction", Prentice Hall, 1989.

Appendix 3: "House Building Basics", American Plywood Association, revised July 1989.

Appendix 4: "Residential and Commercial APA Design / Construction Guide", American Plywood Association, revised January 1989.

Appendix 5: "Plywood Panel Siding over Rigid Foam Insulation", American Plywood Association Technical Note C465C, July 1987.

Appendix 6: "Condensation: Causes and Control", American Plywood Association Technical Note X485G, February 1990.

Appendix 7: Thorogood, R.P., "Technical Notes on Timber Frame", Building Technology and Management, May 1981.

Appendix 8: "303 Plywood Siding", American Plywood Association Technical Product Guide, August 1988.

Appendix 9: Scalzi, J., "Recommendations of the Workshop on Research Needs for Masonry", Department of Civil Engineering, University of Clemson, S.C. Internal Report, August 1988.

Appendix 10: Anderson, J.M., and Gill, J.R., "Rainscreen Cladding: A Guide to Design Principles and Practice", CIRIA, Butterworths, 1988.

Appendix 11: "Wall Cladding Defects and their Diagnosis", U.K. Building Research Establishment Digest 217, September 1978.

Appendix 12: Raufaste, N.J., "Building Technology Project Summaries 1989", NISTIR 89-4068, U.S. Department of Commerce, April 1989.

BIBLIOGRAPHY

1. *Olin, H.B., Schmidt, J.L., and Lewis, W.H., Constrution: Principle, Materials and Methods, Van Nostrand Reinhold, 5th edition, 1990.*

2. *Mann, P.A., Illustratrd Residential and Commercial Construction, Prentice Hall, 1984.*

3. *American Plywood Association, Home Building Basics, P.O. Box 11700, Tacoma, WA 98411-0700, revised July 1989.*

4. *American Plywood Association, APA Design/construction Guide: Residential & Commercial, P.O.Box 11700, Tacoma, Washington 98411-0700, revised edition January 1989.*

5. *Condensation - Causes and Control, America PLywood Association Technical Note X485G, P.O.Box 11700, Tacoma, WA 98411-0700, February 1990.*

6. *Thorogood, R.P., "Timber External Walls: Is there a risk of decay from moisture?", Building Technology and Management, May 1981.*

7. *A Builder's Guide to Energy Efficient Homes in Georgia, Governor,s Office of Energy Resources, Atlanta, GA, March 1990.*

8. *Emery, J., "Exterior Finishes on Plywood and Composite Panels," American Plywood Association Resources Report 140, APA, P.O.Box 10700, Tacoma, WA. 0700.*

9. *Building Research Establihment Digest 251, Assesment of damage to low-rise buildings, BRE Watford, U.K., July 1981.*

10. *Scalzi, J., "Research needs for Masonry: Recommendations of the Workshop on Research on Research Needs for Masonry", Department of Civil Engineering, Clemson University, August 1988.*

11. *Brookes, A. J., Grech, C., The Building Envelope: Applications of New Technology Cladding, Butterworth Architecture Press, 1990.*

12. *Anderson, J.M., and Gill, J.R., "Rainscreen Cladding: A Design Guide to Design Principles and Practice", CIRIA Building and structural Design Report, Butterworths, 1988.*

13. *Gilleard, J.D., Myers, J., and Olatidoye, O.A., "Computer Applications in Architectural Conservation", ACADIA 90 conference, Boulder, CO, September 1990.*

14. *"Draft Report: Life-cycle cost data for exterior wall systems, Council for Masonry Research, 1990.*

15. *Peterson, S.R., "A User's Guide to the Building Life-Cycle Cost Computer Program", ASTM Publication, revised edition 1990.*

16. *Raufaste, N.J., "Building Technology Project Summaries 1989", NISTIR 89-4068 Report, U.S. Department of Commerce, April 1989.*